carbon
sequestration leadership forum

6th CSLF Ministerial Meeting
Riyadh, Saudi Arabia
November 1-5, 2015

Carbon Sequestration Leadership Forum

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6th CSLF MINISTERIAL MEETING DOCUMENTS BOOK

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Carbon Sequestration Leadership Forum

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6th CSLF Ministerial Meeting

Riyadh, Kingdom of Saudi Arabia

01-05 November 2015

	Sunday 01 November 2015	**Monday 02 November 2015**	**Tuesday 03 November 2015**	**Wednesday 04 November 2015**	**Thursday 05 November 2015**
Morning		CSLF Technical Group Meeting	CSLF Policy Group Meeting CSLF Stakeholders Meeting (*continues*)	Ministerial Conference and Roundtable	Visit to Saudi Aramco's Dhahran Facility (*intended for Ministers and Heads of Delegations only*)
Afternoon	Task Force Meetings	CSLF Technical Group Meeting (*continues*) CSLF Stakeholders Meeting	CSLF Policy Group Meeting (*continues*)	Ministerial Conference and Roundtable (*continues*)	Visit to Dhahran (*continues*)
Evening		Dinner		Dinner	

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Draft: 05 October 2015
Prepared by CSLF Secretariat

Agenda

CSLF PROJECTS INTERACTION AND REVIEW TEAM (PIRT)

Four Seasons Hotel
Riyadh, Saudi Arabia
01 November 2015

14:00-17:00

1. **Welcome and Opening Remarks**
   Andrew Barrett, Acting PIRT Chair, Australia

2. **Introduction of Attendees**
   Meeting Attendees

3. **Adoption of Agenda**
   Andrew Barrett, Acting PIRT Chair, Australia

4. **Approval of Summary from Regina PIRT Meeting**
   Andrew Barrett, Acting PIRT Chair, Australia

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

   Richard Lynch, CSLF Secretariat

6. **Review of Project Nominated for CSLF Recognition:**
   CO_2 Capture Project, Phase 4
   Nigel Jenvey, CCP Chairman

7. **Review of Project Nominated for CSLF Recognition:**
   CO2CRC Otway Project – Stage 2
   Maxwell Watson, Project Developer – CO_2 Storage, CO2CRC

8. **Review of Project Nominated for CSLF Recognition:**
   Oxy-Combustion of Heavy Liquid Fuels Project
   Tidjani Niass, Chief Technologist, Saudi Aramco

9. **Review of Project Nominated for CSLF Recognition:**
   Carbon Capture and Utilization Project / CO_2 Network Project
   Atieh Abu Raqabah, General Manager, Saudi Arabia Basic Industries Corp. (SABIC)

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10. Future PIRT Activities

- Technology Workshops
- Future TRM Progress Reports
- 2017 TRM

Andrew Barrett, Acting PIRT Chair, Australia

11. Open Discussion and New Business

Meeting Attendees

12. Action Items and Next Steps

Richard Lynch, CSLF Secretariat

13. Closing Comments / Adjourn

Andrew Barrett, Acting PIRT Chair, Australia

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CSLF-T-2015-05
Draft: 23 October 2015
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Technical Group Meeting

Four Seasons Hotel
Riyadh, Saudi Arabia

Monday, November 2, 2015

08:00-09:00 Meeting Registration

09:00-10:30 Technical Group Meeting

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

2. **Meeting Host's Welcome**
   Khalid Abuleif, Sustainability Advisor to the Minister, Ministry of Petroleum and Mineral Resources, Saudi Arabia

3. **Introduction of Delegates**
   Delegates

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

5. **Review and Approval of Minutes from Regina Meeting** CSLF-T-2015-04
   Trygve Riis, Technical Group Chair, Norway

6. **Report from Secretariat**
   - Review of Regina Meeting Action Items
   - Highlights from June 2015 Mid-Year Meeting
   - Technical Group Deliverables for Ministerial

   Richard Lynch, CSLF Secretariat

7. **Overview of CCS Activities in Saudi Arabia**
   Ali Al-Meshari, Manager, EXPEC Advanced Research Center, Saudi Aramco

8. **Update on CO_2 GeoNet and CGS Europe Projects**
   Isabelle Czernichowski, CGS Europe Coordinator, BRGM

10:30-10:45 Refreshment Break

10:45-12:30 Continuation of Meeting

9. **Overview of Alstom's Oxyfuel Development Program**
   Magnus Mörtberg, CCS/CCU Marketing Manager, Alstom

10. **Update from the IEA Greenhouse Gas R&D Programme**
    Tim Dixon, Manager – Technical Programme, IEAGHG

11. **Report from Projects Interaction and Review Team**
    Andrew Barrett, Acting PIRT Chair, Australia

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12:30-13:30 **Lunch**

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

12. Review of Project Nominated for CSLF Recognition:
CO_2 Capture Project – Phase 4
Nigel Jenvey, CCP Chairman

13. Review of Project Nominated for CSLF Recognition:
CO2CRC Otway Project – Stage 2
Maxwell Watson, Project Developer – CO_2 Storage, CO2CRC

14. Review of Project Nominated for CSLF Recognition:
Oxy-Combustion of Heavy Liquid Fuels Project
Tidjani Niass, Chief Technologist, Saudi Aramco

15. Review of Project Nominated for CSLF Recognition:
Carbon Capture and Utilization Project / CO_2 Network Project
Atieh Abu Raqabah, General Manager,
Saudi Arabia Basic Industries Corp. (SABIC)

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

15:45-17:45 **Continuation of Meeting**

16. Report from Sub-Seabed Storage of CO_2 Task Force CSLF-T-2015-06
Mark Ackiewicz, Task Force Chair, United States

17. Decisions on Future Technical Group CSLF-T-2015-07
Action Plan Activities
Mark Ackiewicz, Action Plan Working Group Lead, United States
Delegates

18. Update from Joint Task Force on the Development of CSLF-T-2015-08
2^{nd} and 3^{rd} Generation CCS Technologies
Lars Ingolf Eide, Task Force Co-Chair, Norway
Geoff Murphy, Task Force Co-Chair, Canada

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

20. Election of Technical Group Chair and Vice Chairs CSLF-T-2015-09
Presiding: Richard Lynch, CSLF Secretariat

21. Update on Future CSLF Meetings
Richard Lynch, CSLF Secretariat

22. Open Discussion and New Business
Delegates

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

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

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF-P-2015-05
Draft: 26 October 2015
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Policy Group Meeting

Four Seasons Hotel
Riyadh, Saudi Arabia

Tuesday, November 3, 2015

08:00-09:00 Meeting Registration

09:00-10:15 Policy Group Meeting

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

2. **Meeting Host's Welcome**
   Khalid Abuleif, Sustainability Advisor to the Minister, Ministry of Petroleum and Mineral Resources, Saudi Arabia

3. **Introduction of Delegates**
   Delegates

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

5. **Review and Approval of Minutes from Regina Meeting** — CSLF-P-2015-04
   Christopher Smith, Policy Group Chair, United States

6. **Review of Regina Meeting Action Items**
   Jarad Daniels, Director, CSLF Secretariat

7. **Consideration of Applications for CSLF Membership** — CSLF-P-2015-06
   Delegates

8. **Report from CSLF Technical Group**
   - Highlights from Technical Group Meeting
   - Projects Nominated for CSLF Recognition

   Trygve Riis, Technical Group Chair, Norway

10:15-10:30 Refreshment Break

10:30-12:00 Continuation of Meeting

9. **Report from the CCS in the Academic Community Task Force** — CSLF-P-2015-07
   Wolfgang Heidug, Advisor, King Abdullah Petroleum Studies and Research Center (KAPSARC)

10. **Report from the CSLF Capacity Building Governing Council**
    William Christensen, Capacity Building Governing Council Chair, Norway

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11. Discussion of Committee Work Plan Status:

a. Financing for CCS Projects
Bernard Frois, France
Delegates

World Business Council on Sustainable Development (WBCSD) Low Carbon Technology Partnership Initiative (LCTPi)
TBD representative from the WBCSD

b. Supporting Development of 2nd and 3rd Generation CCS Technologies CSLF-P-2015-08
Trygve Riis, Technical Group Chair, Norway
Geoff Murphy, Canada
Delegates

12:00-13:00 Lunch

13:00-15:00 Continuation of Meeting

c. Global Collaboration on Large-Scale CCS Projects
Jarad Daniels, Director, CSLF Secretariat
Delegates
TBD representatives from major CCS projects

d. Communications
Khalid Abuleif, Saudi Arabia
Delegates

12. IEA CCS Activities Update
Juho Lipponen, International Energy Agency

13. Global CCS Institute Update
Victor Der, Global CCS Institute

14. Report from CSLF Stakeholders
Barry Worthington, United States Energy Association
Other Stakeholders TBD
Delegates

15:00-15:30 Refreshment Break

15:30-17:30 Continuation of Meeting

15. 2015 CSLF Ministerial Meeting
Khalid Abuleif, Saudi Arabia
Jarad Daniels, Director, CSLF Secretariat
Delegates

16. Review of Draft 2015 CSLF Ministerial Communiqué
Jarad Daniels, Director, CSLF Secretariat
Delegates

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17. **Review of Policy Group Messages to Ministers**
Chris Smith, Policy Group Chair, United States

18. **Election of Policy Group Chair** CSLF-P-2015-09
Jarad Daniels, Director, CSLF Secretariat

19. **Update on Future CSLF Meetings**
Jarad Daniels, Director, CSLF Secretariat

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

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

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

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CARBON SEQUESTRATION LEADERSHIP FORUM

RIYADH, SAUDI ARABIA

2015 STAKEHOLDER AGENDA

The Carbon Sequestration Leadership Forum (CSLF) is a Ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for the separation and capture of carbon dioxide (CO_2) for its transport and long-term safe storage. The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical, economic, and environmental obstacles. The CSLF will also promote awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies.

The CSLF is currently comprised of 23 members, including 22 countries and the European Commission. CSLF member countries represent over 3.5 billion people, or approximately 60% of the world's population.

Membership is open to national governmental entities that are significant producers or users of fossil fuels and that have a commitment to invest resources in research, development and demonstration activities in CO_2 capture and storage technologies.

Members of the carbon sequestration stakeholder community are involved with the CSLF and are encouraged to participate and interact with the CSLF.

The CSLF Charter, established in 2003, establishes a broad outline for cooperation with the purpose of facilitating development of cost-effective techniques for capture and safe long-term storage of CO2, while making these technologies available internationally.

CSLF Members

- Australia
- Brazil
- Canada
- China
- European Commission
- France
- Germany
- Greece
- India
- Italy
- Japan
- Korea
- Mexico
- Netherlands
- New Zealand
- Norway
- Poland
- Russia
- Saudi Arabia
- South Africa
- United Arab Emirates
- United Kingdom
- United States

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2015 STAKEHOLDER AGENDA

Monday November 2, 2015

12:00 – 13:30	Lunch
13:30 - 14:00	Michael Moore, North American Carbon Capture Storage Association-NACCSA
14:00 - 14:30	Victor Der, Acting General Manager – The Americas, Global CCS Institute (GCCSI)
14:30 – 15:00	Edward Dodge, Clean Energy Writer and Consultant
15:00 – 15:30	Andrew Purvis, General Manager – Europe, Middle East and Africa, Global CCS Institute
15:30 – 15:45	Refreshment break
15:45 – 16:15	Frank Ennenbach, Director of Technology and R&D for Environmental Control System, Alstom
16:15 – 16:45	Shihsir Tamotia, India Advisor, Jupiter Oxygen
16:45 – 17:15	Hussain Abdulla Al Musawa, Technical Services Department Manager, FERTIL

Tuesday November 3, 2015

09:00 – 09:30	David Hone, Chief Climate Change Advisor, Shell
09:30 – 10:00	Nigel Jenvey, Manager, BP Group Technology & Chair, CO2 Capture Project
10:00 – 10:30	Dr. Timothy “Tip” A. Meckel, Research Scientist, Bureau of Economic Geology, The University of Texas at Austin
10:30 – 10:45	Refreshment Break
10:45 – 11:15	Dr. Noah Diech, Founder and Executive Director, Center for Carbon Removal, UC Berkeley Energy and Climate Institute
11:15 – 12:00	Ammar A. AlNahwi, Manager, Research & Development, Saudi Aramco - Saudi Aramco Carbon Management Activities
12:00 – 12:30	Discussion CSLF Stakeholders Message to Ministers
12:30 – 13:30	Lunch

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Carbon Sequestration Leadership Forum

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MINISTERIAL CONFERENCE

4 NOVEMBER 2015

OPENING PLENARY SESSION

Moving Beyond the First Wave of CCS Demonstrations

08:30-09:00 **Welcome**
Ernest Moniz, Secretary of Energy, United States, & CSLF Ministerial Co-Chair

Host Country Address
Ali bin Ibrahim Al-Naimi, Minister of Petroleum and Mineral Resources, Saudi Arabia, & CSLF Ministerial Co-Chair

Ministerial Introductions
Ministers

09:00-09:30 **Scene-Setting Presentations**

- **Global Role of CCS**
  Kamel Ben Naceur, Director for Sustainable Energy Policy and Technology, International Energy Agency (IEA)
- **Role of CCS in the Middle East**
  Nadhmi A. Al-Nasr, Executive Vice President, King Abdullah University of Science and Technology (KAUST), Saudi Arabia

09:30-09:50 **History and Opportunity of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC)**
Christian Friis Bach, Under-Secretary-General of the United Nations, & Executive Secretary of the United Nations Economic Commission for Europe (UNECE)

09:50-10:15 **Refreshment Break**

10:15-13:00 **Roundtable Session 1: Steps to Complete and Move Beyond the First Wave of CCS Demos – How Fast is Reasonable?**
Chair: Suhail Mohamed Faraj Al Mazrouei, Minister of Energy, United Arab Emirates

- **Shell Quest Project in Canada**
  David Hone, Global Climate Change Advisor, Shell
- **SaskPower Boundary Dam Project in Canada**
  Michael Monea, President of CCS Initiatives, SaskPower
- **Illinois Industrial CCS Project in the United States**
  Scott McDonald, Biofuels Development Director, Archer Daniels Midland
- **Occidental Petroleum's CO_2 Enhanced Oil Recovery Business in the United States**
  James Briscoe, Senior Vice President of Development, Occidental Petroleum
- **Uthmaniyah CO_2-EOR Project in Saudi Arabia**
  Khaled A. Al-Buraik, Vice President, Petroleum Engineering and Development, Saudi Aramco
- **Rotterdam Storage and Capture Demonstration Project (ROAD) in the Netherlands**
  Hans Schoenmakers, Director Stakeholder Management, Maasvlakte CCS Project C.V.

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Roundtable Session 2: National and International Policies to Accelerate the Deployment of CCS
Chair: Ali bin Ibrahim Al-Naimi, Minister of Petroleum and Mineral Resources, Saudi Arabia

- **Norway's CCS Efforts**
  Tord Lien, Minister of Petroleum and Energy, Norway
- **The Netherland's CCS Efforts**
  Henk Kamp, Minister of Economic Affairs, Netherlands
- **U.S. CCS Policy Under President Obama's Climate Action Plan**
  Ernest Moniz, Secretary of Energy, United States

13:00-14:30 **Participants Lunch**
Separate Ministers-Only Lunch

AFTERNOON SESSION

Key Actions Needed for CCS at the 2015 United Nations Climate Change Conference (COP21) to Ensure a Clean Energy Future

14:30-15:00 **Key CSLF Perspectives**

- **Stakeholders**
  Barry Worthington, Executive Director, United States Energy Association (USEA)
- **Technical Group**
  Trygve Riis, Technical Group Chair, Norway
- **Policy Group**
  Christopher Smith, Policy Group Chair, United States

15:00-16:00 **CSLF Ministerial Discussion: Opportunities/Key Policies and Actions Needed for CCS Deployment**
Chair: Ernest Moniz, Secretary of Energy, United States

- *Summary of the Roundtables*
- *Statements / Remarks from Ministers*
- *Potential Actions Identified*

16:00-17:00 **CLOSED SESSION - Ministerial Communiqué**

17:00-17:30 **Press Conference**

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CSLF-T-2015-04
Revised Draft: 21 September 2015
Prepared by CSLF Secretariat

DRAFT

Minutes of the Technical Group Meeting

Regina, Saskatchewan, Canada
Tuesday, 16 June 2015

LIST OF ATTENDEES

Chair	Trygve Riis (Norway)

Delegates

Australia:	Clinton Foster (*Vice Chair*), Maxwell Watson
Canada:	Stefan Bachu (*Vice Chair*), Eddy Chui, Geoff Murphy, Kathryn Gagnon
China:	Sizhen Peng, Xian Zhang
European Commission:	Jeroen Schuppers, Stathis Peteves
France:	Didier Bonijoly
Italy:	Giuseppe Girardi, Sergio Persoglia
Japan:	Ryozo Tanaka, Takashi Kawabata
Korea:	Chang Keun Yi, Chong Kul Ryu
Mexico:	Jazmin Mota
Netherlands:	Paul Ramsak
Norway:	Jostein Dahl Karlsen, Lars Ingolf Eide
Poland:	Anna Madyniak
Saudi Arabia:	Khalid Abuleif, Hamoud AlOtaibi, Fahad Almuhaish
South Africa:	Landi Themba (*Acting Vice Chair*)
United Kingdom:	Philip Sharman, Brian Allison
United States:	Mark Ackiewicz, Stephanie Duran

Representatives of Allied Organizations

Global CCS Institute:	Neil Wildgust
IEAGHG:	Tim Dixon

CSLF Secretariat

Richard Lynch, Adam Wong

Invited Speakers

Michael Monea, President, Carbon Capture and Storage Initiatives, SaskPower
John Schadan, President – Canada Operations, Westmoreland Coal Company
Eddy Chui, Director, Clean Fossil Fuels, CanmetENERGY, Natural Resources Canada
Mark Crombie, CCP3 Programme Manager, BP Group Technology
David Bernier, Senior Principal Power Discipline Leader, Stantec
Jinfeng Ma, Jingbian CCS Project Lead, Northwest University (China)
Edward S. Rubin, Professor and Founding Member, Department of Engineering and Public Policy, Carnegie Mellon University
Wayne Rowe, Senior Project Manager, Schlumberger
Jonathan Carley, Vice President – Business Development, CO_2 Solutions, Inc.

Observers

Canada:	Chunjiang An, Scott Hendrigh, Brett Henkel, Matt Nasehi, Simon O'Brien, Scott Pittendrigh, Luc Rock, Floyd Wist, Kyle Worth, Zewei Yu
China:	Wei Wang
Korea:	Sung-ho Jo
Norway:	Britta Paasch, Åse Slagtern
United Kingdom:	Aatif Baskanderi, Bill Buschle
United States:	Richard Esposito, Robert Hilton, Scott McDonald, Ed Steadman

1. Chairman's Welcome and Opening Remarks

The Chairman of the Technical Group, Trygve Riis, called the meeting to order and welcomed the delegates and observers to Regina. Mr. Riis mentioning that this is an important meeting because it prepares the Technical Group for the upcoming 6th CSLF Ministerial, in Saudi Arabia in November, and that some of the items on the agenda are directly relevant to the Ministerial.

Mr. Riis stated that two currently active task forces will be providing updates, as will the Projects Interaction and Review Team which has researched and developed a draft Interim Report on the CSLF Technology Roadmap. This Interim Report, once finalized, will be a Technical Group deliverable at the Ministerial. Another deliverable for the Ministerial will be a report on supporting development of 2nd and 3rd generation CO_2 capture technologies. This is one of the four main initiatives of the Policy Group's action plan and the report on this topic will be prepared jointly with the Policy Group.

In closing, Mr. Riis also mentioned that the current meeting is perhaps the most content-rich of any Technical Group meeting ever, with many presentations of interest to attendees. This includes a presentation about the Jingbian CCS Project, which has been nominated by China and Australia for CSLF recognition.

2. Meeting Host's Welcome

Michael Monea, President of SaskPower's Carbon Capture and Storage Initiative, provided a brief welcoming message for the CSLF meeting. CCS is now in a critical period, where the large-scale first-of-a-kind projects like SaskPower's Boundary Dam Project are showing that it is possible for coal-fueled power plants to have very low carbon emissions. Mr. Monea stated CSLF recognition for the Boundary Dam Project has provided it an additional level of positive attention, and he hoped the visit to the project later in the week would be enlightening.

3. Introduction of Delegates

Technical Group delegates present for the meeting introduced themselves. Sixteen 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, Saudi Arabia, South Africa, the United Kingdom, and the United States. Observers representing Canada, China, Korea, Norway, the United Kingdom, and the United States were also present.

4. Adoption of Agenda

The Agenda was adopted with the small change of rearranging the order of two presentations in the morning session because of a schedule conflict for one of the invited speakers.

5. Approval of Minutes from Warsaw Meeting

The Minutes from the October 2014 Technical Group Meeting were approved with no changes.

6. Report from CSLF Secretariat

Richard Lynch provided a report from the Secretariat which covered the status of action items from the October 2014 meeting in Poland and some of the highlights from that meeting.

Mr. Lynch stated that there were six Action Items from the October 2014 meeting, five of which are now complete. There was one deferred Action Item, where Australia's delegation had been requested to prepare a background paper on how gas stream compositions could affect the performances of CO_2 capture solvents. Discussion of this topic may occur at a future Technical Group meeting. In addition to these Action Items, consensus was reached by the Technical Group on the following items:

- The Norcem CO_2 Capture Project is recommended by the Technical Group to the Policy Group for CSLF recognition. (*note: The project received CSLF recognition at the Policy Group's meeting two days later*.)
- 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 IEAGHG.

Concerning the October 2014 meeting, Mr. Lynch mentioned that the overall meeting included a site visit to the lignite-fueled Bełchatów Power Plant in central Poland. Bełchatów is the largest thermal power plant in Europe and accounts for 20% of Poland's total electricity production. An 858-megawatt unit at the power plant has been made

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CCS-ready but the project has not moved forward due to cost and public acceptance issues. The site visit included an extensive Q&A session with power plant management, which provided a much better understanding of why the project is on hold.

7. Coal's Perspective in a CCS Environment

John Schadan, President of Westmoreland Coal Company's Canada Operations, provided a short presentation on how the coal industry perceives CCS. Westmoreland is currently the 6th largest coal producer in North America and supplies fuel for more than coal-fired units, fifteen of which are in the western Canadian provinces of Alberta and Saskatchewan.

Mr. Schadan stated that with the global push toward a low-carbon future, coal producers have a stake in the success of CCS. In Canada, stringent federal emissions standards have made power companies look away from conventional coal-fueled power plants for new electricity sources, but commercialization of CCS would allow coal to remain a part of the fuel mix. This will be important in the next several decades, as existing coal-fueled units in Canada reach the end of their mandated 50-year lifetime. The long-term survival of the coal industry will depend on innovations like CCS to allow the continued use of coal, and the manner in which coal and power industries engage their stakeholders will play a large part on how broadly inclusive solutions are developed. Mr. Schadan closed his presentation by also mentioning that continued R&D is essential and that countries should continue to support development of the new generation of CCS technologies that will maintain coal's relevancy as a cost-effective fuel.

8. Overview of CCS Activities in Canada

Eddy Chui, Director of CanmetENERGY's Clean Fossil Fuels Program at Natural Resources Canada, gave a presentation that summarized Canada's extensive ongoing CCS program and related activities. Canada's overall strategy for advancing CCS includes implementing large-scale demonstration projects to prove technologies while learning-from-doing, sharing Canadian knowledge and expertise outside of Canada, improving the CCS business case through development of 2nd and 3rd generation CCS technologies, and promoting innovation in Canada's clean energy technology sector. Canada has been a leader in the CCS field with more than three decades of RD&D experience. Since 2008, the Canadian Government has invested more than C$580 million in R&D and large-scale projects, with provincial governments contributing another C$1.2 billion in funding. Additionally, the provincial utility SaskPower has invested more than C$2 billion in CCS, which has resulted in its Boundary Dam Project.

Dr. Chui stated that there are currently four large-scale CCS projects in Canada that are in operation or under construction. Besides the Boundary Dam Project, which began operations in October 2014, the Weyburn-Midale Project has been in operation since the year 2000. The Quest Project is expected to begin operations before the end of 2015 and the Alberta Carbon Trunk Line Project is scheduled to be operational in 2017. In addition, the Aquistore Project, which commenced operations earlier in 2015, is a large-scale project which has created permanent storage for CO_2 from the Boundary Dam Project.

Dr. Chui also provided a sampling of the CCS projects and activities being supported by private sector companies in Canada. These include Saskatchewan-based HTC CO_2 Systems, which has a pilot project for testing an advanced post-combustion CO_2 capture process, Quebec-based CO_2 Solutions, which is developing an enzyme-enabled CO_2

capture technology, British Columbia-based Inventys Thermal Technologies, which is working toward pilot-scale demonstrations of a new post-combustion CO_2 capture technology, Nova Scotia-based CarbonCure Technologies, which has developed a technology for sequestering CO_2 in concrete, and SaskPower, which has built a new CO_2 capture test facility for evaluation of amine-based post-combustion technologies. In addition, the Government of Canada, through Natural Resources Canada, is also supporting a portfolio of CCS-related technologies under development, and these include pressurized oxyfuel combustion, supercritical CO_2 turbines, pressurized chemical looping combustion, and CO_2 utilization.

Dr. Chui closed his presentation by stating that Canada has parlayed its natural CCS advantage and strong R&D foundation into a position of global leadership, and is contributing to the global effort to advance CCS. Going forward, Canada's focus will be on strengthening the CCS business case through continued R&D, while collaborating with key international partners and participation in multilateral organizations such as the CSLF.

9. Update from the IEA Greenhouse Gas R&D Programme (IEAGHG)

Tim Dixon gave a presentation about the IEAGHG and its continuing collaboration with the CSLF's Technical Group. The IEAGHG 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 IEAGHG 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 next one in November 2016 in Switzerland.

Mr. Dixon mentioned that since 2008 the IEAGHG 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 mutual representation of each at CSLF Technical Group and IEAGHG Executive Committee (ExCo) meetings, and also the opportunity for the Technical Group to propose studies to be undertaken by the IEAGHG. These, along with proposals from IEAGHG ExCo members, go through a selection process at semiannual ExCo meetings. So far there have been four IEAGHG 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), "Potential Implications of Gas Production from Shales and Coal for CO_2 Geological Storage" (November 2013), and "Life Cycle Assessment of Carbon Capture, Utilization and Storage (CCUS) – Benchmarking". This benchmarking study will actually be a workshop with a resulting report, with the workshop taking place in the early part of 2016.

10. Update from the Global Carbon Capture and Storage Institute (GCCSI)

Neil Wildgust provided a concise update on GCCSI's technical focus for 2015 and beyond. The current emphasis is on the cost of CO_2 capture and how CO_2 storage projects can be facilitated and expedited. For CO_2 capture, while it is clear that 1st generation projects will deliver important lessons, it will require continued R&D to develop the 2nd and 3rd generation technologies that are crucial to achieving cost and performance goals for the 2020-2025 timeframe.

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Mr. Wildgust stated that the GCCSI, as part of its report *The Global Status of CCS: 2015* has examined R&D projects globally to determine energy and capital cost impacts that would affect the development and deployment of the next generations of CO_2 capture technologies. These two factors, together, currently account for more than 50% of the increase in cost of electricity that would result from the implementation of CCS at a fossil fuel power plant. Concerning CO_2 storage, Mr. Wildgust stated that the international global warming scenario that would limit the increase to 2°C would require more than 2 gigatonnes storage of CO_2 annually by the year 2030 and more than 7 gigatonnes storage annually by the year 2050. One issue is that greenfield CO_2 storage sites can take up to ten years to assess and characterize, and a bigger issue is that industry currently has no incentive to undertake storage exploration. As part of its *The Global Status of CCS: 2015* report, the GCCSI has accomplished a global review of storage resource assessments and concluded that adequate resources exist to allow commercial deployment for CO_2 storage, but different regions of the world have differing emphases on the types of storage projects that would be achievable. Mr. Wildgust concluded his presentation by mentioning that knowledge sharing is imperative if CO_2 storage is to expeditiously move beyond the current first-of-a-kind generation of demonstration projects, and that the GCCSI has set up a series of knowledge-sharing networks for that purpose.

11. CSLF-recognized CO_2 Capture Project – Phase 3 Results

Mark Crombie, BP Group Technology's Programme Manager for the CO_2 Capture Project (CCP), gave a presentation which provided a detailed overview of the recently-concluded third phase of the project. Mr. Crombie stated that the CCP began in the year 2000 as a partnership of several energy companies, with the overall goal to demonstrate technologies which will reduce the cost and accelerate deployment of CCS. The third phase of the project (CCP3) had the specific objective of producing a fuller picture of the integrated costs for CCS and consisted of four work teams (supported by economic modeling):

- Capture, aimed at reducing the cost of CO_2 capture;
- Storage Monitoring and Verification (SMV), aimed at increasing understanding and developing methods for safely storing and monitoring CO_2 in the subsurface;
- Policy and Incentives, aimed at providing technical and economic insights needed by stakeholders and to keep track of ever-evolving legal and policy frameworks; and
- Communications, aimed at providing outreach of project outcomes to stakeholders and the general public.

Mr. Crombie stated that for CCP3, two CO_2 capture scenarios were developed and examined:

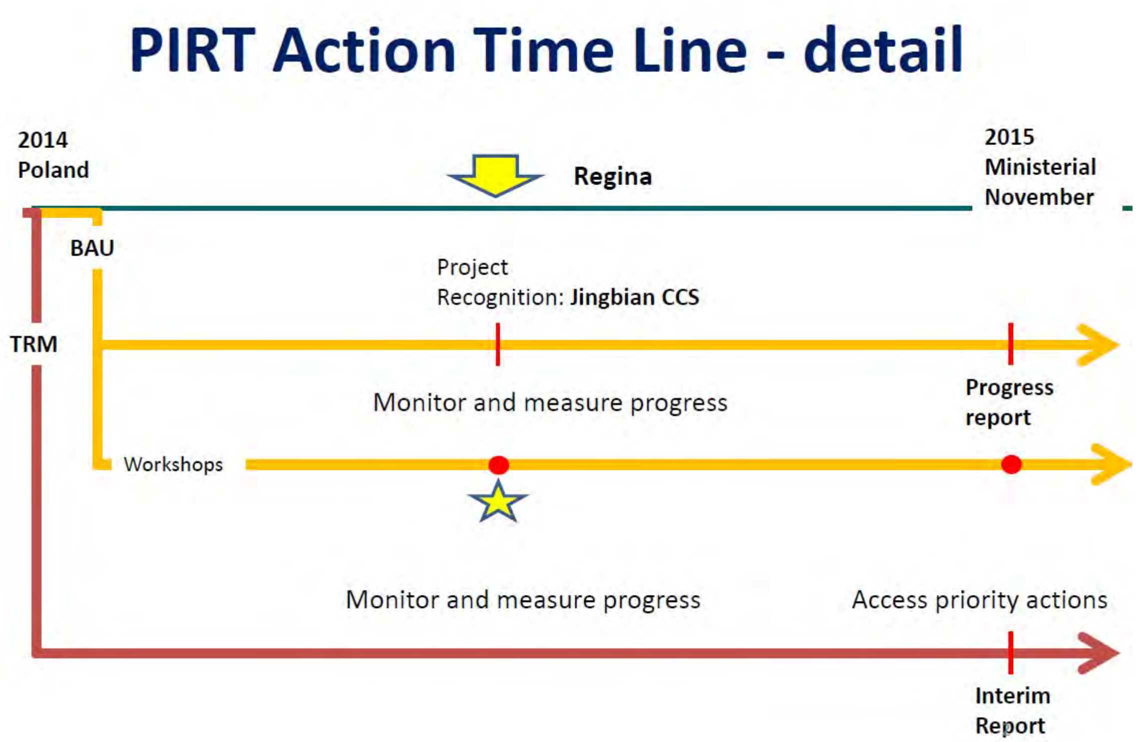
- Field demonstration of fluid catalytic cracking oxy-firing capture technology, with Petrobras in Brazil, which developed operability and scale-up data; and
- Field demonstration of oxy-fired – once-through steam generation, with Cenovus Energy and other partners in Canada, which confirmed the technical viability of the process.

Mr. Crombie mentioned that the SMV Program was comprised of several areas of investigation, including well integrity, subsurface processes, monitoring & verification, and field-trialing. The Policy and Incentives Program is contributing to the development of legal and regulatory frameworks via documentation of project experiences with regulatory processes. The CCP3 Communications Program has promulgated project results via the project website and at conferences and meetings such as this CSLF event.

Concerning the 4th phase of the CCP, Mr. Crombie stated that the focus would be on assessing "breakthrough" technologies that could result in a substantial improvement in CO_2 capture costs. Many of these technologies would be suitable for non-utility use such as in refineries and natural gas operations. The storage part of CCP4 would have an emphasis on well integrity. Mr. Crombie ended his presentation by mentioning that CCP4 activities will build on its previous experience and expertise, and the project will welcome new partners and collaborate with others to ensure continued success.

12. 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. 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 during its previous day meeting, the PIRT had evaluated the Jingbian CCS Project as a first step in the CSLF recognition process and had reviewed the draft TRM Interim Report, whose finalized version will be a deliverable to the upcoming CSLF Ministerial Meeting. The TRM Interim Report is intended to report on ten technology needs areas that were identified by the 2013 edition of the TRM, specifically on the perceived amount of progress being made in each of these areas and on barriers which are inhibiting this progress.

Specific outcomes from the meeting were:

- The PIRT recommends approval by the Technical Group for the Jingbian CCS Project.
- The PIRT believes that the draft TRM Interim Report needs a substantial rewrite.

Concerning the second outcome, Dr. Foster stated that the draft report was deficient because perceived progress in any of the ten technology needs areas was being inexactly described due to adverse influences by economic and policy barriers. For instance, the draft TRM Interim Report, taking into account all kinds of barriers, indicates that 1st generation technologies to conduct large-scale CO_2 storage were perceived as showing only very slow to moderate progress for being developed and implemented. However, from a purely a technical viewpoint, actually there are no significant technology barriers in this area. Several delegates pointed out that this disconnect most likely occurred because the survey questionnaire asked for evidence-based opinions on “progress in both application and adaptation” of CCS technologies and not “technology readiness”. Another problem with the draft report is that 2nd and 3rd generation concepts, described in the report, do not apply to all ten technology needs areas.

There was extended discussion on what kinds of remedial actions were needed and in the end, the following plan was adopted:

- The TRM Interim Report will be rewritten, incorporating new information about the current status of technology for the ten technology needs areas.
- The PIRT working groups who wrote the ten sections describing progress for the technology needs areas will solicit opinions from world-class experts in these areas, from purely a technology viewpoint, on the degree of technical readiness.
- The Secretariat will collect these expert opinions and use them to produce new graphics for the report.
- The PIRT working groups which wrote the ten sections will also do the re-writes of these sections. The rewrites will de-emphasize 2nd and 3rd generation technologies (including removal of the graphics for 2nd and 3rd generation technologies) and eliminate any descriptions that are not applicable or relevant.
- The Secretariat will coordinate the overall rewrite process and do any rewrites to other parts of the report. The goal is for a new draft to be completed by about the end of August.

Technical Group delegates were also requested to provide the Secretariat their comments on the existing draft of the report by the end of August.

13. Full-Scale Design of a Post-Combustion CO_2 Capture Process for a Gas-Fired Plant

David Bernier, Senior Principal Power Discipline Leader for Stantec, gave a luncheon presentation that described concept study details for the planned CCS project at Statoil’s Mongstad facility in Norway. The gas-fueled power plant at Mongstad was to have been a combined heat and power (CHP) facility, producing 280 megawatts of electricity and 350 megawatts of thermal energy. Mr. Bernier stated that a comprehensive evaluation of the CCS project, including an engineering feasibility study, a technology qualification program, and an engineering concept (pre-FEED) study, was conducted over about a two year period before the project was terminated.

Concerning the pre-FEED study, Mr. Bernier stated that the engineering scope included many different modules: flue gas handling, the CO_2 removal and compression systems, waste water treatment, the power distribution system, solvent storage, and the cooling water system. The technical approach focused on critical equipment, and utilized 3D modeling which resulted in a realistic design that would have facilitated construction of the project. The pre-FEED study also included numerous health and safety reviews, which were inputs to the site safety plan. Mr. Bernier illustrated his presentation with timeline depictions of the construction process, and concluded by stating that even though this project in the end did not go forward, it still resulted in useful information that could be beneficial in the design of future similar large-scale CCS projects.

14. Review and Approval of Project Proposed for CSLF-Recognition: Jingbian CCS Project

Jinfeng Ma, representing Northwest University of China, gave a presentation about the Jingbian project. This integrated large-scale pilot project, located at a coal-to-chemicals company in the Ordos Basin of China's Shaanxi Province, is capturing CO_2 from a coal gasification plant via a commercial chilled methanol process, transporting the CO_2 by tanker truck to a nearby oil field, and utilizing the CO_2 for EOR. The overall objective is to demonstrate the viability of a commercial EOR project in China. The project includes capture and injection of up to about 50,000 tonnes per year of CO_2. There will also be a comprehensive measurement, monitoring and verification (MMV) regime for both surface and subsurface monitoring of the injected CO_2. This project is intended to be a model for efficient exploitation of Shaanxi Province's coal and oil resources, as it is estimated that more than 60% of stationary source CO_2 emissions in the province could be utilized for EOR.

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

15. Final Report from Task Force on Review of CO_2 Storage Efficiency in Deep Saline Aquifers

Task Force Chair Stefan Bachu provided a brief update on the task force and its results. 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 which can be stored in a unit of aquifer pore volume

Dr. Bachu stated that one of the main findings of the task force is that storage efficiency depends on many different elements. These include aquifer characteristics (many of them), operation characteristics (many of them), and regulatory constraints (e.g., "do not exceed" limitations). Another finding was that for atlas-type estimates of CO_2 storage resource at the aquifer/basin scale, storage efficiency coefficients of 2-3% should be used for P50 confidence. Further, for local-scale evaluations of CO_2 storage capacity, numerical (dynamic) estimates should be used, taking into account that storage capacity is pressure limited.

Dr. Bachu stated that a paper titled "Review of CO_2 Storage Efficiency in Deep Saline Aquifers", authored by himself, will be published in the September 2015 issue of *The*

International Journal of Greenhouse Gas Control, and this paper serves as the task force's final report. Dr. Bachu concluded his presentation by stating that the task force ended its activities in the 4th quarter of 2014 and has now disbanded.

16. Report from Task Force on Technical Barriers and R&D Opportunities for Offshore, Sub-Seabed Storage of CO_2

Task Force Chair Mark Ackiewicz gave a brief update on the task force and its activities. 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. Ackiewicz stated that the task force developed a draft outline of its final report in June 2014 and provided a status report to the Technical Group at its October 2014 meeting. Since then, a first draft of the final report has been completed and is under review by task force members.

Mr. Ackiewicz provided information about the report's structure, which will include sections on all aspects of sub-seabed CO_2 storage such as resource assessments, CO_2 transport aspects, wellbore management, risk analysis, monitoring tools, and regulatory requirements. Also, there will be a set of recommendations concerning knowledge-sharing, storage capacity assessments, CO_2 transport infrastructure, offshore CO_2-EOR, understanding of CO_2 impacts on the subsea environment, and monitoring technology development. Mr. Ackiewicz concluded his presentation by mentioning that there have been a total of 28 members on this task force, representing six countries and four continents. The various task force members are affiliated with government agencies, universities, research laboratories, industry, and non-governmental organizations, making this both the largest and most diverse task force ever for the Technical Group.

17. Report on the ISO and its CCS-related Activities

Tim Dixon gave a short presentation about the International Organization for Standardization's Technical Committee on CO_2 Capture, Transportation and Geological Storage (ISO/TC 265). This committee was convened in 2011 with the mission of preparing standards for the design, construction, operation, environmental planning, risk management, MMV, and other activities related to CCS. Mr. Dixon stated that there are currently six working groups, each with its own set of activities. The standards development procedure works through consensus and is a multi-stage process. New work item proposals are first made into a working draft, and those that gain consensus from the working group are made into a committee draft. At that point a greater degree of working group consensus is required to move the proposal into the "draft international standard" phase, which then requires a comments period and consensus of the working group's panel of experts to become an ISO standard.

Mr. Dixon stated that the ISO/TC 265 currently includes nineteen participating countries, nine observer countries, and also seven liaison organizations (including the CSLF). The committee as a whole has met five previous times since its formation with the sixth meeting scheduled for September 2015 in Norway.

18. The Outlook for Improved Carbon Capture Technology

Edward S. Rubin, Professor and Founding Member of Carnegie Mellon University's Department of Engineering and Public Policy, gave a presentation that described the potential for future improvements for CO_2 capture and what it would take to achieve them. Prof. Rubin stated that there are two principal measures of progress in CO_2 capture technology: improvements in performance (e.g., higher capture efficiencies, lower energy penalties, increased reliability, and reduced life cycle impacts) and reductions in cost (e.g., capital cost, cost of electricity, cost of CO_2 avoided, and cost of CO_2 captured). Most improvement goals now focus on cost reduction, and a recent cost update study has found there have actually been significant increases in CO_2 capture cost since the time of the IPCC's Special Report on CCS (2005), even after adjusting all costs to constant 2013 US$.

Prof. Rubin stated that there are three main ingredients for technology innovations that would reduce CO_2 capture costs: sustained R&D, markets for the technology, and especially, learning from experience with full-scale projects. Experience has shown that dramatic improvements in other low-carbon technologies and for other technologies for power plant emissions reductions have occurred once wide deployment of these technologies has occurred. Currently, the key barriers to global CCS deployment are policy-related. Without a policy requirement or strong incentive to reduce CO_2 emissions significantly, there is no reason to deploy CCS widely. Prof. Rubin closed his presentation by offering that although sustained R&D is essential to achieve lower CO_2 capture costs, learning from experience is actually the critical step. And in the end, it will be strong policy drivers to create markets for CCS that will spur innovations for significantly reducing the cost of CO_2 capture.

19. Well Injectivity Lessons Learned at SaskPower's Aquistore Project

Wayne Rowe, Senior Project Manager for Schlumberger, provided a short technical status report on SaskPower's Aquistore Project, which focused on lessons learned and obstacles overcome while developing the CO_2 injection well. The project's injection well goes down to 4,300 meters in depth and passes through many different geologic layers to get to the four saline aquifer injection zones. The overall injection rate is determined by a series of injectivity tests which determine the maximum pressure at which the well can be operated during injection (typically 90% of the fracture pressure), and therefore the maximum CO_2 injection rate.

Mr. Rowe stated that during the initial injectivity test, in September 2012, a pressure spike occurred (the cause of which was not understood) that resulted in one of the four zones no longer being able to accept CO_2, and this greatly reduced the CO_2 injection rate. Three years later the test was repeated, with the result that whatever had happened to cause this problem had not gone away. However, a diversion treatment of the well using ping-pong balls was able to seal perforations into the zones where pressure spikes had occurred which resulted in a much greater injectivity into the favored injection zones. Mr. Rowe concluded by stating that the overriding lessons learned from this experience on how to overcome problems of this nature would benefit future injection projects.

20. Enzymatic Technology for Low-Cost Carbon Capture

Jonathan Carley, Vice President of Business Development for CO_2 Solutions, gave a presentation that described a novel method for CO_2 capture that utilizes a robust bio-engineered carbonic anhydrase enzyme as the capturing agent. This process improves on conventional liquid-phase CO_2 capture processes as it reduces the process energy requirement and does not create waste products. Mr. Carley stated that the process is now being demonstrated at pilot-scale (10 tonnes CO_2 capture per day) on the flue gas from a natural gas-fueled boiler (8.3% CO_2 content). Initial results have shown a 90% capture rate. The cost of capture (including compression to 2,250 psi) has been estimated at C$39 per tonne, which would be a significant improvement over current commercial CO_2 capture processes.

Mr. Carley ended his presentation by summarizing some of the advantages of this new process: it utilizes an environmentally benign solvent, there is a smaller footprint for the capture unit than for conventional processes of the same scale, the solvent regeneration uses heat outside of the power plant steam cycle, and as a result there will be a lower total cost of CO_2 capture. Mr. Carley stated that the pilot plant, located near Montreal, is scheduled for 2,500 hours operation (which began in May 2015) and is open for visits by any interested parties.

21. Review of Technical Group Action Plan

Trygve Riis stated that the Secretariat had prepared a short update on the status of the Technical Group's Action Plan, and that after the end of 2015, if no new activities are initiated, the only ongoing task force would be the PIRT. In that regard, it would therefore be beneficial to expand the Technical Group's activities into some new areas. An extensive discussion ensued, with the outcome that a new working group was formed to develop additional Action Plan activities. Members of this working group are Australia (Maxwell Watson), Norway (Lars Ingolf Eide), Saudi Arabia (Ahmed Aleidan), the United Kingdom (Brian Allison and Philip Sharman), and the United States (Mark Ackiewicz). The CSLF Secretariat will assist in coordinating the working group's activities as needed. The working group was asked to complete its activities in time for the upcoming CSLF Ministerial.

22. Update from Joint Task Force on the Development of 2nd and 3rd Generation CCS Technologies

Lars Ingolf Eide provided a status update on the Joint Policy-Technical Task Force on "Supporting Development of 2nd and 3rd Generation CCS Technologies". This task force has been established with Norway as the lead for the Technical Group and Canada the lead for the Policy 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. Eide stated that a report is being prepared which will summarize existing information in the area of 2nd and 3rd generation CO_2 capture technologies, and that the report is being organized to provide descriptions of the technologies and their development pathways as well as information on existing CCS test centers where some of these technologies could be scaled-up. Due to resource and time limitations, the report groups technologies into four categories: post-combustion, pre-combustion, oxy-combustion, and other emerging technologies. Individual technology summaries provide a description of the technology, an assessment of its maturity, a description of challenges it faces, a list of the companies and organizations that are involved in development, a description of the kinds of R&D still needed for maturity, any environmental impacts of the technology, and the types of industries where the technology could see use. Mr. Eide stated that the report does not address the economics for use of these technologies but does show technology readiness levels. Completion of the report is expected in time for the Ministerial meeting. At the conclusion of Mr. Eide's presentation, there was agreement that Secretariat will circulate a copy of the report-in-progress to all Technical Group delegates, and that the delegates will provide any comments, additions and corrections to Mr. Eide by the end of August.

Following Mr. Eide's update, Geoff Murphy gave a short presentation that described a proposed new section of the CSLF website that would track the development of 2nd and 3rd generation CO_2 capture technologies. This new section, to be created and maintained by the CSLF Secretariat, would highlight technology approaches and existing test facilities. Mr. Murphy provided that the new section would also include the task force's definitions of what constitutes a 2nd generation and a 3rd generation technology.

It was also proposed that this new section also include information on technology providers, but several delegates were skeptical about how well such a section on technology providers could be developed and maintained, in terms of both completeness and accuracy. Philip Sharman pointed out that the proposed country-by-country approach is not always adequate as some technology providers are multinational. In the end there was agreement that the Secretariat should, for now, create new website sections for technology approaches and test facilities, with the allowance that it would be a continuing work in progress and information would be added as it becomes available.

Kathryn Gagnon then gave a short presentation that highlighted the policy context for advancement of 2nd and 3rd generation technologies. As a background, Canada's delegation had brought in a consultant who interviewed 35 individuals representing eight countries and a variety of organizations to provide insight on what policy barriers existed for inhibiting progress on these technologies, what success factors were in place for advancing the technologies, and what mechanisms would be useful for accelerating development of the technologies. Ms. Gagnon stated that results from this process showed that there were already some mechanisms, such as carbon pricing and loan guarantees, which were helping the first generation of technologies make it to the demonstration phase but there were currently no real market drivers for CCS. The existence of test centers was considered critical to the development of newer and more advanced technologies as these reduce the costs for testing these technologies at larger scales. Even more critical, the existence of country initiatives such as Norway's CLIMIT Program are providing a pathway for technology developers for development and scale-up, including funding opportunities. Ms. Gagnon closed her presentation by stating that she would expand on these themes at the upcoming Policy Group meeting.

23. Technical Group Deliverables for 6th CSLF Ministerial Conference

Richard Lynch provided a short summary on Technical Group deliverables to the upcoming Ministerial Conference. Four documents are anticipated: the TRM Interim Report, the report on "Supporting Development of 2nd and 3rd Generation CO_2 Capture Technologies" (though an executive summary may be the specific deliverable to the Ministers), a paper describing outcomes from the upcoming "Lessons Learned from Large-Scale CCS" Technology Workshop (*note: successfully held on June 17th*), and a "Messages and Recommendations from the CSLF Technical Group" document which would bring together results and outcomes from various other Technical Group task forces and events. Mr. Lynch also stated that unlike what happened at the previous Ministerial Meeting in 2013, this time the Technical Group will have a much greater presence at the Ministerial Conference including a seat at the table and an item on the agenda.

24. Update on International CO_2 Capture Test Centre Network

Lars Ingolf Eide gave a short presentation on the status of the International CO_2 Capture Test Centre Network, which was officially launched in 2013 to accelerate CCS technology development. Mr. Eide stated that the network's main function is to facilitate knowledge sharing of operational experience and non-confidential information, and that analysis and problem solving (and *not* data collection) is the network's focus. Criteria for a test facility's membership in the network is that the facility must be operating on real flue gas (i.e., be connected to a power plant or industrial plant), it must have the intent of being neutral in any technology decisions, it must be willing to share information and receive visitors, and it must be willing to pay a membership fee. Some of the fee money is being used to support workshops.

Mr. Eide stated that there have been three previous workshops, in Mongstad, Norway in May 2014 (which was focused on amine-based post-combustion capture), in Austin, Texas, U.S.A., in October 2014 (which was an exchange of experiences on how best to measure and model amine emissions), and in Wilhelmshaven, Germany in April 2015 (which was focused on aerosols and mist formations). The next workshop will be in Regina in September 2015 as part of the IEAGHG Post-Combustion Capture Conference. Future knowledge-sharing topics may include health, safety and the environment (HSE), instrumentation and monitoring, waste management, comparing baselines, and promoting technology certification and standardization. Mr. Eide concluded his presentation by mentioning that the network is actively pursuing new members and seeks to establish liaisons with other CCS-related networks.

25. Update on Future CSLF Meetings

Richard Lynch provided a short summary of upcoming CSLF events, beginning with the next day's "Lessons Learned from Large-Scale CCS" technology workshop. Mr. Lynch stated that the workshop will have two sessions, on siting / construction and operation, with eight large-scale projects represented. Concerning the 6th CSLF Ministerial Meeting, being hosted by the Kingdom of Saudi Arabia's Ministry of Petroleum and Mineral Resources in Riyadh, Mr. Lynch stated that the event would be a five day meeting, organized as follows:

- Sunday, November 1: task force meetings
- Monday, November 2: Technical Group meeting
- Tuesday, November 3: Policy Group meeting
- Wednesday, November 4: Ministerial Conference
- Thursday, November 5: site visit (*intended for Ministers and heads of delegation*)

Mr. Lynch stated that further details concerning the Ministerial would be forthcoming soon. Hamoud AlOtaibi expanded on this outline by mentioning that the Ministerial Conference will include a public-private roundtable and that the site visit on November 5th would be to Saudi Aramco facilities in Dhahran. Mr. AlOtaibi also mentioned that there would be an exhibition area, where companies and CSLF member countries can showcase their CCS-related technologies and projects.

For the 2016 CSLF meetings, Mr. Lynch stated that there was nothing yet to report concerning the mid-year meeting but Japan may be willing to host the year-end annual meeting. Takashi Kawabata was called on for additional comments and welcomed the opportunity to bring the CSLF to Japan. Mr. Kawabata stated that a budgetary request for the meeting has been made, so Japan's hosting of the 2016 CSLF Annual Meeting should be considered tentative at this point with a final decision expected by the end of the year.

26. Farewell to Two Friends

Earlier in the meeting there was a short appreciation of two retiring CSLF delegates. This was the last meeting for two of the Technical Group's Vice Chairs, Stefan Bachu and Clinton Foster. Richard Lynch expressed gratitude from the Secretariat for the tremendous amount of proactiveness and leadership they have provided the CSLF and said that it had been a privilege to have worked with them. Trygve Riis presented Dr. Bachu and Dr. Foster each with a gift to recognize and honor their years of service to the CSLF. The meeting attendees bid farewell to Dr. Bachu and Dr. Foster with a round of applause.

27. Review of Consensuses Reached and Action Items

Consensus was reached on the following items:

- The Jingbian CCS Project is recommended by the Technical Group to the Policy Group for CSLF recognition.
- The Technical Group will form a working group to develop additional Action Plan activities. Members of the working group are Australia, Norway, Saudi Arabia, the United Kingdom, and the United States.
- The Technical Group will revise the TRM Interim Report, incorporating new information about the current status of technology for the identified ten technology needs areas.

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 Jingbian Project be recognized by the CSLF. (*Note: this was done at the June 18th Policy Group meeting.*)
2	The ten PIRT working groups	Obtain expert opinions on technology readiness for the technology needs areas identified in the TRM. Once new graphics are available, do rewrites of the ten technology sections of the TRM Interim Report, de-emphasizing 2nd and 3rd generation technologies (including removal of the graphics for 2nd and 3rd generation technologies) and eliminating any descriptions that are not applicable or relevant.

Item	Lead	Action
3	Secretariat	Coordinate the rewrite of the TRM Interim Report, including developing new graphics based on expert opinions about technology readiness and doing any re-writes that are needed for other parts of the report.
4	Secretariat	Send a copy of the draft Joint Policy-Technical Task Force report on "Supporting Development of 2nd and 3rd Generation CCS Technologies" to Technical Group delegates for their comments.
5	Technical Group delegates	Provide any comments, additions, and corrections on the draft Joint Policy-Technical Task Force report on "Supporting Development of 2nd and 3rd Generation CCS Technologies" to the task force co-chair.
6	Action Plan Working Group	Develop ideas for additional Action Plan activities in time for the 6th CSLF Ministerial.
7	Secretariat	Create new section on CSLF website for tracking progress on 2nd and 3rd generation CO_2 capture technologies.

28. Closing Remarks / Adjourn

In adjourning the meeting, Trygve Riis expressed his appreciation to the meeting host SaskPower, the CSLF Secretariat, the meeting sponsors, and all the meeting attendees. Richard Lynch recognized SaskPower's Sandra Beingessner as having provided a tremendous amount of effort in making the meeting happen.

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 the upcoming Ministerial meeting. Mr. Riis then reminded attendees of the next day's technology workshop and adjourned the meeting.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2015-06
20 October 2015

TECHNICAL GROUP

Final Report from Task Force on Technical Barriers and R&D Opportunities for Offshore, Sub-Seabed Geologic Storage of CO_2

Background

At the March 2014 CSLF Technical Group Meeting in Seoul, the Technical Group formed a new Task Force to identify technical barriers and R&D needs/opportunities for offshore, sub-seabed storage of CO_2. The Task Force presented interim reports at the October 2014 Technical Group meeting in Warsaw and the June 2015 Technical Group meeting in Regina.

This paper represents the final report from the Task Force.

Action Requested

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

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Technical Barriers and R&D Opportunities for Offshore, Sub-Seabed Geologic Storage of Carbon Dioxide

Report Prepared for the Carbon Sequestration Leadership Forum (CSLF) Technical Group

By the Offshore Storage Technologies Task Force

September 14, 2015

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ACKNOWLEDGEMENTS

This report was prepared by participants in the Offshore Storage Task Force: Mark Ackiewicz (United States, Chair); Katherine Romanak, Susan Hovorka, Ramon Trevino, Rebecca Smyth, Tip Meckel (all from the University of Texas at Austin, United States); Chris Consoli (Global CCS Institute, Australia); Di Zhou (South China Sea Institute of Oceanology, Chinese Academy of Sciences, China); Tim Dixon, James Craig (IEA Greenhouse Gas R&D Programme); Ryozo Tanaka, Ziqui Xue, Jun Kita (all from RITE, Japan); Henk Pagnier, Maurice Hanegraaf, Philippe Steeghs, Filip Neele, Jens Wollenweber (all from TNO, Netherlands); Philip Ringrose, Gelein Koeijer, Anne-Kari Furre, Frode Uriansrud (all from Statoil, Norway); Mona Molnvik, Sigurd Lovseth (both from SINTEF, Norway); Rolf Pedersen (University of Bergen, Norway); Pål Helge Nøkleby (Aker Solutions, Norway) Brian Allison (DECC, United Kingdom), Jonathan Pearce, Michelle, Bentham (both from the British Geological Survey, United Kingdom), Jeremy Blackford (Plymouth Marine Laboratory, United Kingdom). Each individual and their respective country has provided the necessary resources to enable the development of this work. The task force members would like to thank John Huston of Leonardo Technologies, Inc. (United States), for coordinating and managing the information contained in the report.

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EXECUTIVE SUMMARY

This report provides an overview of the current technology status, technical barriers, and research and development (R&D) opportunities associated with offshore, sub-seabed geologic storage of carbon dioxide (CO_2). Specifically, the report includes:

- Existing and proposed offshore storage and enhanced oil recovery (EOR) projects.
- The current status of offshore CO_2 storage and EOR resource capacity assessments.
- Current status of transport, wellbore/well construction, and monitoring technologies, the potential challenges, and R&D opportunities.
- Existing and proposed regulatory requirements.
- Risk analysis tools and methodologies and R&D opportunities.
- Recommendations for further action.

While onshore geologic storage has been emphasized in many carbon capture and storage (CCS) projects, offshore storage provides several advantages:

- Near-offshore capacity is globally significant and information where available from oil and gas exploration and production provides a good understanding of the offshore geology.
- There is a single owner and manager of both mineral and surface rights.
- Risks to freshwater aquifers are less of a concern.
- Existing pipeline rights-of-way for oil and gas production could facilitate CO_2 pipeline infrastructure development.
- For federally-owned storage resources, revenues could be generated from offshore carbon storage activities.
- Monitoring technologies exist, but there is potential for improvement.

However, there are several challenges that exist, some of which are similar to onshore storage activities:

- Containment risks presented by existing wells.
- Protection of competing economic and environmental interests: for example, commercial fisheries, sensitive ecosystems, and existing and undiscovered gas resources need protection.
- Elevated costs: Despite existing offshore pipelines, costs of operating offshore projects are likely to be significantly higher than those onshore, as experience from decades of oil and gas extraction regionally indicate.
- Accessibility: Some near-offshore regions may have unique development challenges related to infrastructure development.
- Impact of CO_2 on marine ecosystems: Much work has identified the ongoing risks of ocean acidification via CO_2 absorption from the atmosphere, and the more localized impacts from well leakage were less understood but these are being studied and there is a growing body of knowledge.

Today, there are only a handful of offshore storage projects that are currently injecting CO_2 into saline formations: the Sleipner and Snøhvit projects in Norway, and the K-12B project off the coast of the Netherlands. There is also one CO_2-EOR project that is operational in Brazil. However, about a dozen more projects have been proposed, including projects in Japan, China, the United Kingdom, and the Netherlands. These projects play an important role in understanding the offshore storage environment and application of CCS in an offshore setting.

The key recommendations from the report can be categorized into five areas, which are storage capacity assessments, transport infrastructure, offshore CO_2-EOR potential and opportunities, understanding CO_2 impacts on the subsea environment, and monitoring technology development.

Storage Capacity Assessments: It would help prospective CCS stakeholders if public-private partnerships were developed to provide a number of pre-qualified storage locations. For such locations, all preparatory work, including the documents for a storage permit application could be made available to reduce the uncertainty regarding the availability of storage. This would support both the storage and the transport elements of CCS projects.

It is recommended that a more thorough evaluation of the geologic storage aspects of many basins be pursued. It is also recommended that an increased level of knowledge sharing and discussion be implemented among the international community to outline the potential for international collaboration in offshore storage.

Transport Infrastructure*:* The CO_2 transportation infrastructure must increase significantly and will be an important contributor to the overall costs for CCS. Hence, optimization of current practices is important, on areas such as CO_2 product specifications and sharing of infrastructure to optimize utilization.

Additionally, during the pilot and demonstration phase of CCS, CO_2 volumes will be relatively small. However, these projects could be developing the first elements of the large-scale infrastructure, if sufficient incentive is given to oversize the components of the transport infrastructure. Especially during the early phase of CCS, public-private partnership is essential to generate these large infrastructural works.

An increase in the available financial incentives for (offshore) CCS projects is needed to increase the speed of development of offshore CCS. Funding mechanisms should consider funding operational costs, as well as up-front investments.

Offshore CO_2-EOR: Offshore CO_2-EOR is seen as a way to catalyze storage opportunities and build the necessary infrastructure networks. One of the barriers reported widely for offshore CO_2-EOR projects is the investment required for the modification of platform and installations, and the lost revenue during modification. Recent advances in subsea separation and processing could extend the current level of utilization of sea bottom equipment to also include the handling of CO_2 streams. By moving equipment required to separate and condition the CO_2 to the seafloor, modifications to the platform can be minimized. It is recommended that RD&D activities explore opportunities to leverage existing infrastructure and field test advances in subsea separation and processing equipment.

Understanding CO_2 Impacts on the Subsea Environment: It is recommended to expand upon modeling efforts to understand CO_2 dispersion in an ocean environment. Whilst the primary driver of the spatial extent of detectability and impact is the leakage rate, many other factors such as depth, bubble size, current speed, tidal mixing and topography are shown to have a large influence on dispersal. Existing models are robust, but limited in that they generally cannot deal with very fine scales (≈1 meter) which are necessary for the correct treatment of small leak scenarios at the same time as accurately defining regional scale mixing processes, necessary for the correct estimation of dispersion. Model development of marine systems is required to improve their predictive capabilities. Advances are needed so that systems can simulate leakage in the context of natural variability by combing both pelagic and benthic dispersion and chemistry, including carbonate and redox processes. There is also a need to develop models that can simulate large scale dispersion of multi-phase plumes whilst simultaneously simulating tidally-induced dispersion in the near and far field.

Monitoring Technology Development: Deep-focused monitoring relies heavily on established hydrocarbon industry tools which are mature. There is scope for improving some of these technologies and related data processing and interpretation for CO_2 storage. The quantification of CO_2 distribution within a reservoir still remains a challenge.

Shallow-focused monitoring is less advanced compared with deep focused monitoring, but systems are being developed and demonstrated. New marine sensor and existing underwater platform technology such as automated underwater vehicles (AUVs) and mini-remotely operated vehicles (Mini-ROVs) enable deployment and observation over large areas at potentially relatively low cost. Seafloor and ocean monitoring technologies can detect both dissolved phase CO_2 and precursor fluids (using chemical analysis) and gas phase CO_2. AUV technology capable of long-range deployment needs to be developed so that the AUV can be tracked transmit data via a satellite communications system. Real-time data retrieval and navigation will enable onshore operators to modify or refine surveys without costly intervention using a survey vessel. Further development in integrated in situ sensors has been underway over the last 5 years. The quantification of leakage at the seabed remains a technical challenge.

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1 Introduction

1.1 CSLF Purpose

The Carbon Sequestration Leadership Forum (CSLF) is a Ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for the separation and capture of CO_2 for its transport and long-term safe storage. The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical, economic, and environmental obstacles. The CSLF will also promote awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies.

The CSLF comprises a Policy Group and a Technical Group. The Policy Group governs the overall framework and policies of the CSLF, and focuses mainly on policy, legal, regulatory, financial, economic and capacity building issues. The Technical Group reports to the Policy Group and focuses on technical issues related to Carbon, Capture, Utilization and Storage (CCUS) and CCUS projects in member countries.

The Technical Group has the mandate to identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity, and establish and regularly assess and inventory of the potential areas in need of research.

At the CSLF Ministerial meeting held in Seoul, South Korea in March 2014, the CSLF Technical Group formally moved forward with a task force to identify technical barriers and R&D needs/opportunities for offshore, sub-seabed storage of carbon dioxide, in addition to carbon capture and storage technologies that have been the main focus of CSLF efforts since its inception in 2003.

1.2 Task Force Mandate

The United States proposed to serve as chairperson and lead a Technical Group Task Force that is focused on identifying the Technical Barriers and R&D Opportunities for Offshore, Sub-Seabed Geologic Storage of CO_2. The Task Force will develop a report that will:

- Identify existing projects and characterization activities worldwide on offshore CO_2 storage and progress to date;
- Provide a current assessment or understanding (using available analyses) on the status of global offshore storage potential (including potential for offshore enhanced oil recovery [EOR]);
- Identify the technical barriers/challenges to offshore CO_2 storage (e.g., characterization, monitoring, transport challenges and R&D opportunities;
- Identify potential opportunities for global collaboration; and

- Include conclusions and recommendations for consideration by CSLF and its member countries.

1.3 Advantages and Challenges of Offshore CO_2 Storage

Much of the prospective geologic storage on Earth is found where thick sequences of sediments have accumulated on the margins of continents. These accumulations form the below-sea-level geographical features known as continental shelves. The sediments of continental shelves can be expected to contain large volumes of high quality storage related to three recurrent characteristics: (1) shallow sediments which are geologically young so that in many cases the inter-grain pores are well preserved (not filled with cement or extensively damaged by heating, compaction, and deformation), providing large volumes of storage, (2) the seal rocks in the confining system are likewise relatively young and ductile, and have not been as extensively deformed and fractured as is typical of sediments in older basins, and (3) the sediments tend to be thick with abundant sandstones due to passive margin subsidence during sediment accumulation commonly sourced by large river systems draining continental interiors. Other thick sub-sea sediment accumulations that form in settings such as carbonate platforms and rift basins may have similar geologic characteristics. The quality of the storage in these settings is demonstrated by a concentration of abundant large gas reservoirs. Storage in depleted hydrocarbon reservoirs in these sediments may also be attractive in the near term to reduce risks. To extend the possible subsea storage capacity, injection into permeable basalt sequences may also be considered.

The types of storage assessed in this review rely on injection into permeable rocks more than a kilometer below the seafloor and isolation from the surface by impermeable rocks. It is important to separate this storage type of geological CO_2 storage from a number of other types of proposed sub-sea or marine storage that lack these conditions; for example such as CO_2 storage in hydrates or as dense liquid on the seafloor, or as these phases within the upper 100s of meters of seabed sediment (e.g., House et al., 2006[1]), or storage via CO_2 dissolution in deep marine water (e.g., Herzog, 2001[2]).

Many countries are recognizing the potential of offshore geological storage. The European Union's plans to utilize the North Sea for storage are well developed and storage targets show high

[1] House, K.Z., Schrag, D.P., Harvey, C.F., and Lackner, K.S., 2006, Permanent carbon dioxide storage in deep-sea sediments, Proceedings of the National Academy of Sciences, 103(33): 12291-12295.

[2] Herzog, H.J., 2001, What future for carbon capture and storage?, Environmental Science and Technology, 35(7): 148A-153A, DOI: 10.1021/es012307j.

geologic suitability.[3,4] Academic and consultancy studies have addressed the potential of the North Sea for CCS.[5,6] Statoil's Sleipner project in the North Sea has documented the effectiveness of storage in this setting.[7] A second offshore CCS project conducted by Statoil, Snøhvit, has been operational since 2008. In 2009, Australia formally released 10 offshore acreage tracts for CCS consideration, signaling its support of offshore-project development. Studies in Victoria (Gippsland Basin) have highlighted that region's offshore storage prospects.[8] Traditional strengths in marine geosciences have allowed Japanese researchers to develop research programs related to geologic characterization and monitoring techniques for offshore CCS projects.[9] The 2010 NETL carbon sequestration atlas[10] includes estimates of storage capacity in the northern Gulf of Mexico (GOM) and offshore of the Carolinas, indicating nationally significant storage resources. Other recent work to identify storage potential has been initiated along the eastern US (New Jersey shelf and the Carolinas), and offshore Los Angeles in the Wilmington Graben.

1.3.1 Offshore advantages

In many areas, the best quality and largest volume settings for storage are offshore. The potential geologic advantages are summarized above. Offshore storage has widely-recognized public acceptance, policy, and resource utilization advantages compared to onshore. Instances of local public opposition to onshore projects in Europe (e.g., the proposed Shell project in the Dutch town of Barendrecht) have increased reliance on sub-sea resources, with European storage focus strongly on the North Sea.

Onshore, the abundance of fresh-water resources that must be protected adds to public concern, regulatory burden, and potential liability. Fresh water generally does not extend far offshore reducing concern in offshore settings. In some jurisdictions, the increase in interest in offshore

[3] Chadwick R.A., and Eiken, O., 2013, Offshore CO_2 storage: Sleipner natural gas field beneath the North Sea (Chapter 10). In: Gluyas, J. and Mathias, S. (eds) Geological storage of carbon dioxide (CO_2) – Geoscience, technologies, environmental aspects and legal frameworks. Woodhead Publishing Ltd. ISBN 978-0-85709-427-8, p. 227–250.

[4] Lu, J., Wilkinson, M., Haszeldine, R.S., and Fallick, A.E., 2009, Long-term performance of a mudrock seal in natural CO_2 storage, Geology, 37(1):35-38, doi: 10.1130/G25412A.1.

[5] Sustainable Energy Ireland, 2008, Energy in Ireland 1990-2007, 2008 Report

[6] Element Energy, 2010, One North Sea. A study into the North Sea cross-border CO_2 transport and storage: Norwegian Ministry of Petroleum and Energy and UK Foreign and Commonwealth Office- North Sea Basin Task Force, 111 p.

[7] Hermanrud, C., et al., 2009, Storage of CO_2 in saline aquifers—lessons learned from 10 years of injection into the Utsira Formation in the Sleipner area, Energy Procedia, 1: doi:10.1016/j.egypro.2009.01.260.

[8] O'Brien, G.W., et al., 2008, First order sealing and hydrocarbon migration processes, Gippsland Basin, Australia: Implications for CO_2 geosequestration, PESA Eastern Australasian Basins Symposium III, Sydney, 14–17 September.

[9] Magi, M., 2009, Evaluation study of CCS for the mitigation measure of atmospheric CO_2 and ocean acidification by the global carbon cycle model, Geochimica et Cosmochimica Acta, 73(13):A815.

[10] NETL, 2012. The United States 2012 Carbon Utilization and Storage Atlas, 4th ed. U.S. Department of Energy – National Energy Technology Laboratory – Office of Fossil Energy http://www.netl.doe.gov/technologies/carbon seq/refshelf/atlas/

sequestration results partly from perceived uncertainty for onshore sequestration in the legal framework under which CO_2 sequestration will take place, particularly issues related to pore-space ownership and long-term liability.[11] These concerns about CCS can potentially be avoided in offshore settings because the State or Federal government owns the surface, pore space, and mineral rights, thus avoiding conflict between competing ownership rights. International regulations for offshore CCS have been clarified in the context of existing marine regulations.[12] In addition, the government may have a more compelling reason to take on long-term liability for CO_2 sequestered in offshore settings.

Characterization of the geologic site is critical for selecting the properties that will accept and retain large volumes of fluids. Offshore continental shelves have been extensively explored for hydrocarbon resources globally. These data provide the needed regional characterization prior to site selection, and in favorable settings, existing data may be sufficient to locate high quality storage prospects. Because sediments on continental shelves are typically young and actively accumulating, fluids produced by compaction, shale diagenesis and hydrocarbon generation are expelled at leakage points. Seafloor expression of fluid migration is well documented in many places around the world (e.g., Judd and Hovland, 2007,[13] Huang et al., 2009,[14] Cathles et al., 2010[15]). These defined leakage points can be characterized and used to improve certainty of CO_2 retention, as compared to onshore sites where leakage paths may be relict and obscured.

Commonly the implementation of CCS includes an element of monitoring to document that the storage is effective. Offshore seismic monitoring technologies for subsurface geologic activities exist and have been shown to be effective for CCS.[16] Collecting seismic data offshore is typically lower cost per unit area and has reduced error in noise and repeatability relative to onshore, minimizing complications with acquiring time-lapse datasets for monitoring. Towed instruments

[11] Duncan, I. J., Nicot, J. P., and Choi, J. W. (2009). Risk assessment for future CO_2 sequestration projects based CO_2 enhanced oil recovery in the US. *Energy Procedia*, *1*(1), 2037-2042.

[12] Dixon, T., et al., 2009, International marine regulation of CO_2 geological storage—developments and implications of London and OSPAR, Energy Procedia, 1: 4503-4510, doi:10.1016/j.egypro.2009.02.268.

[13] Judd, A. and Hovland, M.,2007. Seabed fluid flow – impact on geology, biology and the marine environment. Cambridge University Press, Cambridge, pp 400. www.cambridge.org

[14] Huang, B., Xiao, X., Li, X., and Cai, D., 2009, Spatial distribution and geochemistry of the nearshore gas seepages and their implications to natural gas migration in the Yiggehai Basin, offshore South China Sea, Marine and Petroleum Geology, 26: 928-935.

[15] Cathles, L.M., Su, Z., and Chen, D., 2010, The physics of gas chimney and pockmark formation, with implications for assessment of seafloor hazards and gas sequestration, Marine and Petroleum Geology, 27: 82-91.

[16] Chadwick, R.A., Noy, D.J., and Holloway, S., 2009, Flow processes and pressure evolution in aquifers during the injection of supercritical CO_2 as a greenhouse gas mitigation measure, Petroleum Geoscience, 15: 59-73.

(e.g., sonar) are capable of detecting seafloor discharges and bubble columns in the seawater,[17] and effects of leakage into the water column can be modeled.[18,19]

To summarize, the potential benefits of utilizing near-offshore regions for CCS are:

1. To the degree that the continental margins are petroliferous, there generally exists a good geologic understanding of the offshore, enhanced by information available from oil and gas exploration and production.
2. The capacity of the near-offshore is globally significant, meaning the storage capacity is generally considered to be high enough to address annual emissions on a decadal timescale (i.e., meet targets and satisfy agreements).
3. There is a single offshore owner and manager of both mineral and surface rights.
4. The offshore typically has few or no economic fresh-water aquifers in the subsurface that count as underground sources of drinking water. This removes one of the most significant risks present for most onshore sequestration sites. However, risks to seawater are alternatively of concern.
5. The absence of population overlying projected CO_2 plumes eliminates broad classes of public health and safety risks (HSE), aside from operational risk to workers.
6. A large number of existing pipeline rights-of-way for oil and gas production could facilitate development of CO_2 pipeline infrastructure, and offshore infrastructure can be re-commissioned for CCS service, postponing sunset costs.
7. For federally-owned storage resources, revenues generated from offshore CCS activities could be used to return benefits to the public for utilization of publically held resources, and to establish funds for long-term monitoring and mitigation if needed. Income streams could also be considered as offsets for reduced taxation.
8. Monitoring techniques are available and may in some instance be superior offshore compared to onshore. Offshore seismic imaging is a mature technology. Other mature and novel techniques are available for monitoring shallow sediments and the water column to detect unexpected leakage.

[17] Espa., S., Caramanna, G., and Bouche, V., 2010, Field study and laboratory experiments of bubble plumes in shallow seas as analogues of sub-seabed CO_2 leakages, Applied Geochemistry, 25: 696-704.

[18] Kano, Y., Sato, T., Kita, J., Hirabayashi, S., and S. Tabeta, 2009, Model prediction on the rise of pCO_2 in uniform flows by leakage of CO_2 purposefully stored under the seabed, International Journal of Greenhouse Gas Control, 3: 617-625.

[19] Kano, Y., Sato, T., Kita, J., Hirabayashi, S., and S. Tabeta, 2010, Multi-scale modeling of CO_2 dispersion leaked from seafloor off the Japanese coast, Marine Pollution Bulletin, 60:215-224.

1.3.2 Offshore challenges and risks

Risks of conducting CCS in offshore geologic settings need to be carefully evaluated and the range of consequences and likelihood of occurrence need to be considered. The potential challenges or risks of utilizing near-offshore regions for CCS include:

1. Containment risks presented by existing wells.[20,21]
2. Protection of competing economic and environmental interests: for example, commercial fisheries, sensitive ecosystems, and existing and undiscovered gas resources need protection (e.g., Brody et al., 2006).
3. Elevated costs: Despite existing offshore pipelines, costs of operating offshore projects are likely to be significantly higher than those onshore, as experience from decades of oil and gas extraction regionally indicate, CCS is an expensive activity anywhere, but more so offshore—unless income streams are available from EOR.
4. Accessibility: Some near-offshore regions may have unique development challenges related to infrastructure development.
5. Impact of CO_2 on marine ecosystems: Much work has identified the ongoing risks of ocean acidification via CO_2 absorption from the atmosphere, and the more localized impacts from well leakage were less understood but these are being studied and there is a growing body of knowledge.
6. Operational challenges mitigating offshore accidents: A careful and thorough approach to offshore CCS development is an anticipated part of developing offshore storage resources.

[20] Huerta, N.J., Checkai, D., and Bryant, S.L., 2009, Utilizing sustained casing pressure analog to provide parameters to study CO_2 leakage rates along a wellbore, SPE #126700.Judd, A., and Hovland, M., 2007, Seabed fluid flow: The impact on geology, biology and the marine environment, Cambridge University Press, ISBN: 9780521819503

[21] Nicot, J.-P., 2009, A survey of oil and gas wells in the Texas Gulf Coast, United States, and implications for geological sequestration of CO_2: Environmental Geology, v. 57, p. 1625–1638

2 Status and barriers of existing and proposed offshore CO_2 storage and EOR projects

2.1 Status and experience from existing offshore CO_2 storage and EOR projects

2.1.1 Offshore CO_2 storage projects

CO_2 geological storage in the offshore environment offers potentially greater opportunities than onshore in most countries globally. Notwithstanding access to more storage sites and increases in a nation's storage capacity, targeting offshore sedimentary basins avoids populated and regulated areas, eliminates risk on impacting underground sources of drinking water, and is likely to be technically easier for exploration, appraisal, and monitoring, measurement, and verification (MMV).

Experience with offshore CO_2 storage projects is reasonably well developed with nearly 20 years since the start of the first industrial-scale CCS project in 1996 at Sleipner, Norway.[22] Subsequently, in 2004 the pilot-scale project K12-B was started,[23] offshore the Netherlands, and then in 2008 CCS operations commenced at the Snøhvit site[24] in the Norwegian Barents Sea, with onshore CO_2 capture, offshore storage linked by a 150km offshore CO_2 pipeline. All these projects involve disposal of CO_2 separated from natural gas, with injection into saline formations (at Sleipner and Snøhvit) or into a depleted gas field (at K12-B).

Since the start of the Snøhvit project, progress in offshore storage has been limited. However, all currently planned large-scale CCS projects in Europe focus on using offshore options. In Asia, especially in the southeast, offshore storage seems to be the most feasible option. Figure 2-1 shows a snapshot of the offshore storage projects in operation, planned and future prospects globally.

Emerging offshore CO_2 storage projects include the Tomakomai CCS demonstration project in Japan (expected to be operational in 2016), two projects in the UK (Peterhead-Goldeneye and White Rose) and one in the Netherlands (ROAD) which are close to FID and project initiation. These are discussed in some detail below.

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[22] Baklid, A, Krobøl R, Owren G., 1996. Sleipner Vest CO_2 disposal, CO_2 injection into a shallow underground aquifer. Paper SPE 36600, presented at the SPE annual technical conference and exhibition, 6-9 October 1996.

[23] http://www.k12-b.info.

[24] Hansen, O., Gilding, D., Nazarian, B., Osdal, B., Ringrose, P., Kristoffersen, J-B., Eiken, O., Hansen, H., 2012. Snøhvit: The history of injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm. *Energy Procedia*, 37, 3565 – 357.

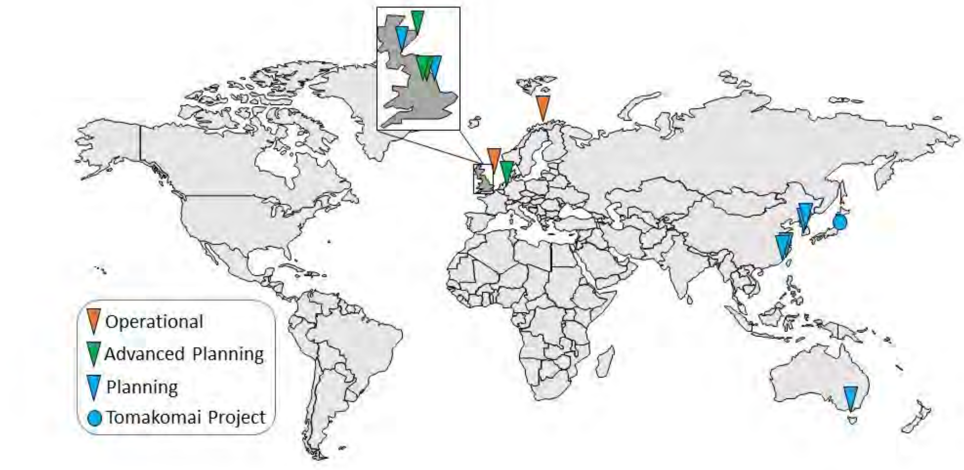

Figure 2-1. Offshore large-scale integrated CCS projects and the Tomakomai Project (Source: Global CCS Institute)

2.1.1.1 Operational projects

Currently, there are three CCS projects with dedicated CO_2 geological storage in operation, as mentioned above: the Sleipner Project, as well as the Snøhvit and K-12-B projects. The Sleipner Project, located about 240 kilometers [km] (149 miles [mi]) west of Stavanger, Norway in central North Sea is associated with natural gas production from primarily the Sleipner East and West gas and condensate fields. The Sleipner East field has low CO_2 content (less than 0.3 percent) but the Sleipner West reservoirs contain gasses with 4-9 percent CO_2.[25] The Sleipner West CO_2 is removed in order to meet the sales gas requirements, and driven by the Norwegian government's CO_2 tax, the CO_2 is injected into a dedicated geological storage site adjacent to the gas fields. The natural gas and CO_2 is separated using the MDEA amine process, compressed and injected from the Sleipner T platform. The CO_2 is injected at a rate of about 0.9 (million metric tonnes per annum) (Mtpa) into the Miocene Utsira Formation, around 1 km below the seafloor and by 2014 more than 15 million metric tonnes (Mt) had been injected and stored. The Project is probably best known for is extensive MMV program, including a series of time lapse (4D) seismic surveys over the storage site. These surveys have provided valuable insights into CO_2 storage behaviour by visualising the movement of the CO_2 plume through the saline formations of the Utsira Formation.

[25] Hansen, H., Eiken, A., and Aasum, T. A. 2005. Tracing the path of carbon dioxide from a gas-condensate reservoir, through an amine plant and back into a subsurface acquifer. Case study: The Sleipner area, Norwegian North Sea. Paper SPE 96742, presented at Offshore Europe 2005, Aberdeen, UK, 6-9 Sept. 2005.

The second operational project, the Snøhvit Project, is located in the Barents Sea, off Norway and began injecting CO_2 in 2008. This LNG development covers three gas fields, Snøhvit, Albatross and Askeladden, which have CO_2 contents ranging from 5 to 8 percent. This fully subsea offshore development pipes the production gas to an onshore gas processing and LNG facility where the CO_2 is separated out due to requirements for the LNG conversion process and also driven by the Norwegian CO_2 tax. The Project includes the world's first offshore pipeline for CO_2 transport which covers some 153 km (95 mi) to link the LNG facility to the subsea template where CO2 injected into saline aquifers adjacent to the Snøhvit gas field. The storage formation is the Jurassic Tubåen and Stø Formations, which are around 2.5 km (1.6 mi) depth below the sea surface. The design capacity is 0.7 Mtpa of CO_2, and by 2014 more than 2.5 Mt had been stored. This project also has an extensive MMV program based on time-lapse seismic and reservoir pressure monitoring, which has proven successful for risk management. During injection in the Tubåen Formation, a gradual increase in well pressure was detected, likely due to previously unknown compartmentalisation of the storage formation. In 2011, re-completion of the injection well was performed and further injection was diverted to the Jurassic Stø Formation.[26]

The K-12-B project, named after the project's offshore platform, also involves CO_2 separated from natural gas and then re-injected into the same reservoir as the gas field, but is smaller scale and defined as a pilot project. It is located in the Netherlands North Sea, around 150 km (93 mi) NW of Amsterdam. Gas production began in 1987 from Permian Slochteren Formation at a depth of around 3.9 km (2.4 mi) below the seafloor. The natural gas CO_2 content is around 13 percent. The CO_2 injection began operation in 2004 and around 0.02 Mtpa of CO_2 is being re-injected into the same reservoir. The project not only tests the effects of CO_2 re-injection and evaluates enhanced gas recovery, but also has an extensive MMV program focused on downhole analysis including fluid sampling and geophysics, as well as using tracers in the injected CO_2 to understand reservoir flow dynamics by sampling the re-produced CO_2.

2.1.1.2 Planned and pilot projects

All four UK/European projects which are in the advanced planning stage target offshore geological storage as part of their CCS operations. However, these new projects involve CO_2 capture from power generation. If and when these projects move to the construction phase, they will represent a dramatic shift globally towards large emission reductions via CCS in the power generation sector. These projects also use a range of capture technologies and fuel sources (gas, coal and biomass) and should help strengthen the validity of offshore CO_2 storage. The most advanced CCS project in this region, The Rotterdam Opslag en Afvang Demonstratie Project (ROAD),[27] in the Netherlands has the potential to be the conduit for emissions of Europe to the North Sea for storage. The project will capture around a quarter of the emissions from a new coal-powered plant, located in the port of Rotterdam. Around 1.1 Mtpa of CO_2 will be transported to a depleted gas field around

[26] Hansen, O., Gilding, D., Nazarian, B., Osdal, B., Ringrose, P., Kristoffersen, J-B., Eiken, O., Hansen, H., [2012] Snøhvit: The history of injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm. Energy Procedia, 37, 3565 – 357.

[27] Huizeling, E., et al., 2011. CCS project development in Rotterdam, Energy Procedia, 4, 5661-5668.

20 km (12 mi) off the coast of Rotterdam. The target reservoir will be TAQA's P18-4 gas reservoir, which will cease production in 2015. An existing well will be re-used to inject into the depleted gas field (Triassic Main Buntsandstein Subgroup) around 3.5 km (2.2 mi) below sea level and has the capacity to store around 35 Mt of CO_2. The ROAD project is the most advanced of any planned CCS projects in Europe with capture and storage permits awarded, but still requiring additional funding to proceed.

The Peterhead-Goldeneye CCS Project will focus on a natural gas fired power station. Located in Aberdeenshire, Scotland, the power station will be retrofitted for post-combustion capture in one (of three) turbines, capturing around 1 Mtpa. CO_2 will be transported 120 km (75 mi) offshore to the depleted Goldeneye gas reservoir, re-using 100 km of pipeline already in place to the existing platform at the site. The depleted field, the Cretaceous Captain Sandstone, is 2.5 km (1.6 mi) below seafloor. The Project's expected start-up is in 2019/2020. Re-using the existing infrastructure will help reduce costs. In addition, it is also expected that the demonstration of the use of a depleted gas field would improve confidence in managing risks.

Figure 2-2. Proposed route for Yorkshire and Humber CCS Country Pipeline in the UK (source: Global CCS Institute; after National Grid Carbon, 2014)

The Don Valley Power Project plans to capture CO_2 from two newly constructed integrated gasification combined cycle power units located in South Yorkshire, UK (Figure 2-2). Expected to start in 2019, approximately 5 Mtpa of CO_2 will be captured and transported to the offshore North Sea via the Yorkshire and Humber CCS Cross Country Pipeline, a common user hub and storage pipeline also to be utilised by the White Rose CCS Project. The White Rose Project is planning to capture around 2 Mtpa of CO_2 in 2019/2020 from an oxy-fuel combustion, coal feedstock (plus biomass) power station in North Yorkshire, United Kingdom. Both Don Valley and White Rose will target the same storage complex, the Triassic Bunter Sandstone Formation, located 70 km (44 mi) off the coast of Yorkshire and about 1 km (3,280 ft) below the seafloor. Utilising a multi-emitter, common-user single 'trunk line' CO_2 pipe to a dedicated storage site has the potential to reduce costs and streamline the CCS project approvals process. If the storage capacity is available, this model could be utilised in many other areas of the world with clustered high emission sources adjacent to storage sites offshore.

The Tomakomai CCS Demonstration Project is presented here as it demonstrates an alternative option to offshore CO_2 storage than detailed above.[28] The Tomakomai CCS Demonstration Project, located in southern Hokkaido, Japan is a medium-scale demonstration project currently under construction. Over 3 years starting in 2016, CO_2 will be captured from a hydrogen production facility at a rate of more than 0.1 Mtpa and piped a short distance to two onshore injection wells, targeting two different storage formations. These wells are highly deviated, extending between 2.9 km (1.8 mi) and 4.3 km (2.7 mi) offshore, to depths of 1.1 km (3,300 ft) and 2.7 km (8,900 ft) below the seabed respectively. The onshore injection to offshore storage option, if proved viable at the commercial-scale could improve the economics of a project where a near shore storage option is available.

Thus, the geological storage of CO_2 in the offshore environment is technically feasible with decades of learnings from not only the oil and gas industry but also dedicated CO_2 storage projects. Comparable to the CCS industry in general, offshore storage is not common practice with only a few projects operational, as detailed above. The exploration and appraisal of a storage site in the offshore environment would be more expensive than onshore but from social, regulatory and technical aspects may actually be easier. Moreover, through the re-use of pipelines and platforms, as well as the re-completion of wells and by targeting depleting/depleted fields or adjacent storage formations, early mover projects could benefit by lowering the overall costs and improving technical viability assurance when a commercial-scale CCS project is proposed. The UK projects in the planning phase are evidence of this and could be a repeated pattern in the offshore environment globally in the future.

2.1.2 Offshore EOR projects

Very few offshore CO_2-EOR projects exist; however, in 2011 Petrobras started the first such project offshore Brazil, as a pilot project in which the supergiant Lula oilfield uses CO_2 separated from natural gas for EOR. The field is in deep water (over 2000 m), below a thick salt formation, at a total depth between 5,000 and 7,000 m. CO_2 is separated from the hydrocarbons produced from the field and re-injected in a pilot to test the feasibility of starting CO_2-EOR early in the lifetime of the field. If successful, this would prevent expensive late-life modifications to platform and installations to accommodate CO_2 processing equipment.[29, 30]

In Southeast Asia, there have been a couple of offshore CO_2-EOR projects. In Vietnam, for example, a small-scale pilot test was conducted at the Rang Dong Oilfield, located 135 km off the coast of Vung Tau, in 2011. In the project, 111 tonnes (t) of CO_2 were injected through an existing

[28] Tanaka, Y., Abe, M., Sawada, Y., Tanase, D., Ito, T., Kasukawa, T., 2014. Tomakomai CCS Demonstration Project in Japan, 2014 Update, Energy Procedia 63, 6111 – 6119

[29] Malone, T., Kuuskraa, V., DiPietro, P., 2014. CO2-EOR Offshore Resource Assessment, report DOE/NETL-2014/1631, 2014, 90 pp.

[30] See: http://www.globalccsinstitute.com/project/petrobras-lula-oil-field-ccs-project.

production well, followed by a four-day oil recovery test with the same well 2 days later. The test was successful and an extended inter-well pilot test is under planning as a next step.[31]

In Europe, the potential for large-scale offshore CO_2-EOR projects is large. In the North Sea, field gas is used on a large scale for enhanced recovery, with total volumes of the order of 35 bcm/yr.[32] A Norwegian sector study[33] pointing to a potential demand for 12-16Mt CO_2 annually for at least 25 years. Several technical feasibility studies for CO_2-EOR, for example at the giant Gullfaks (sandstone)[34] and Ekofisk (chalk)[35] fields, have demonstrated the technical feasibility of large-scale CO_2 injection for EOR offshore. Similar technical potential for CO_2-EOR in the UK offshore sector has also been identified.[36] However, no projects have progressed past the feasibility stage mainly due to economic factors, and most essentially due to the lack of sufficient volumes of CO_2. In order to enable large-scale CO_2EOR in the offshore sector, it is clear that initiatives to initiate CO_2 capture and supply infrastructure are needed.[37]

CO_2-EOR has not yet been commercially implemented in the Gulf of Mexico due to economic (i.e., offshore drilling and pipeline costs) and operational (i.e., recycling facility large footprint) limitations. However, five CO_2-EOR pilots were carried out in Louisiana's shallow near-shore and bay waters back in the 1980s. In all pilots the CO_2 was delivered to the injection site by barges where the CO_2 was injected followed by either nitrogen or field gas in a gravity stable strategy. All pilots were considered successful.[38]

2.2 Barriers to large-scale offshore project demonstration and deployment

The oil and gas industry have been drilling, extracting and injecting in the offshore environment for decades. The technology of the offshore drilling has now been expanded to inhospitable oceans hundreds of meters deep regularly. With the background of several offshore CO_2 storage projects in operation, both at the pilot scale and at an industrial scale (c. 1 Mt CO_2 per annum), it is clear there are no major technical feasibility hurdles or barriers to further deployment. Long-term, safe and secure storage sites can be selected, characterized, operated and completed based on the oil

[31] Ueda, Y. et al., 2013, CO_2-EOR Huff 'n' Puff Pilot Test in Rang Dong Oilfield, offshore Vietnam, Journal of the Japanese Association for Petroleum Technology, Vol. 78, No.2, 188-196

[32] Cavanagh, A., and Ringrose, P., 2014. Improving Oil Recovery and Enabling CCS: A Comparison of Offshore Gas-recycling in Europe to CCUS in North America. Energy Procedia, 63, 7677-7684.

[33] Awan, A. R., Teigland, R., and Kleppe, J., 2008. A survey of North Sea enhanced-oil-recovery projects initiated during the years 1975 to 2005. *SPE Reservoir Evaluation and Engineering*, 11(03), 497-512.

[34] Agustsson H, Grinestaf GH, 2005. A study of IOR by CO2 injection in the Gullfaks field, offshore Norway. In: The 13th European Symposium on Improved Oil Recovery

[35] Hustad, C. W., and Austell, J. M., 2004. Mechanisms and incentives to promote the use and storage of CO_2 in the North Sea. *European Energy Law Report I, Intersentia*, 355-380.

[36] Gozalpour F, Ren SR, Tohidi B., 2005. CO2 EOR and storage in oil reservoirs. *Oil and Gas Science and Technology*, 60, 537-546

[37] Markussen P, Austell JM, Hustad CW., 2002. A CO2-infrastructure for EOR in the North Sea (CENS): macroeconomic implications for host countries. In: The 6th International Conference on GHG Control Technologies, Kyoto, No. 324.

[38] Malone, T., Kuuskraa, V., DiPietro, P., 2014. CO2-EOR Offshore Resource Assessment, report DOE/NETL-2014/1631, 2014, 90 pp.

and gas industries experience in risk management principles. Moreover R&D, pilot, demonstration and operational projects continue to improve our knowledge in the offshore environment in terms of technology, risk management and in particular MMV. The main barriers concern the lack of incentives or business models needed to promote large-scale offshore CO_2 storage.

It is helpful to summarize the main barriers to large-scale offshore CO_2 storage under two classes:

1. Storage in saline formations or depleted gas fields or without any added utilization value for the CO_2 (section 2.1.1);
2. Storage as part of CO_2-EOR where there is some added value via the utilization and storage sequence (section 2.2.2).

2.2.1 Offshore CO_2 storage

The principle barriers to large-scale CO_2 storage in saline formations or depleted gas fields are:

1. Lack of progress with large-scale CO_2 capture projects;
2. Lack of investment in CO_2 transport infrastructure, either via ship or pipeline;
3. Concerns about potential impacts of CO_2 injections on the marine environment;
4. Concerns about the long-term capacity for large-scale CO_2 storage in the offshore setting.

Whilst there are some technical issues underlying these barriers (such as progress with bringing down the cost of CO_2 capture technologies or improving the confidence in monitoring and verification of long-term storage safety), the main issues are financial and societal. There is little doubt that there is a substantial capacity for CO_2 storage offshore,[39,40] where thick accumulations of suitable sedimentary formations are found on the world's extensive continental shelves and margins.

In addition to the barriers listed above, the development of storage sites in saline formations has a long lead time, with significant investment required to prove the feasibility of a storage site.[41] These investments are similar to those of an exploration effort for hydrocarbon fields, with the associated risks, but without the potential benefit of hydrocarbon production. Given the long lead time, exploration for storage sites should precede the development of a capture installation by many years. Uncertainty about the availability of sufficient and proven storage is a key uncertainty for early CCS developers.

From a non-technical or economic perspective the two barriers to the global deployment of CCS with offshore storage targets is the London Protocol and management of fluids in the subsurface across recognized boundaries. The London Protocol precludes the export of wastes, which means

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[39] Schrag, D. P. (2009). Storage of carbon dioxide in offshore sediments. Science, 325(5948), 1658-1659.

[40] Halland, E., Mujezinovic, J., Riis, F., et al., 2014. CO_2 Storage Atlas, Norwegian Continental Shelf. *Petroleum activity on the Norwegian Continental Shelf* www.npd.no/en/Publications

[41] Neele et al., *The SiteChar approach to efficient and focused CO_2 storage site characterisation,* Energy Procedia, 2013.

that CO_2 cannot move across marine borders for the purposes of geological storage. An amendment to enable export for CO_2 storage was adopted in 2009 but only Norway, the UK and The Netherlands have ratified the amendment. On the other hand, the migration of CO_2 in the subsurface, which in some places could potentially move across marine borders was addressed by revising the specific guidelines for CO_2 disposal in 2012. In policy in general, globally the regional and national policy settings of most nations are often fragmented and do not support CCS with offshore deployment.

2.2.2 Offshore CO_2-EOR

In the second class of projects, with storage as part of CO_2-EOR, there is considerable interest in potentially resolving the economic barriers to large-scale CCS, by bringing added value to projects via integrated CO_2-EOR and storage solutions. A number of barriers to the development of offshore CO_2-EOR projects can be identified.

1. Funding mechanisms for capture and transport.
2. A number of studies using different oil and CO_2 price assumptions[42,43] have shown that while CO_2-EOR can provide a positive economic business case for individual projects, the CO_2-EOR incentive still falls significantly short of providing funding mechanisms for CO_2 capture and transport. In a scenario where significant volumes of CO_2 are available from onshore CO_2 capture plants, it could well be the case that CO_2-EOR would improve the overall cost model for integrated CCUS value chain projects.
3. Availability of CO_2: The CO_2 demand of typical North Sea oilfields is of the order of 5 Mt per annum.[44] Until about 2025, the only CO_2 volumes available around the North Sea will be those from pilot and demonstration projects that produce relatively small volumes each (of the order of 1 Mt per annum). Larger volumes, from single point sources, can be expected no sooner than about one decade from today—a typical CCS project development period. Consequently, the first large-scale pipeline from (near-shore) capture locations bringing sufficient and reliable quantities to offshore oilfields are unlikely to appear before that time.
4. Cost of converting existing installations: A final important hurdle to offshore CO_2-EOR projects is that the cost of conversion of existing offshore platform facilities from water or gas injection to CO_2 injection requires a significant upgrading of topside facilities and wells. Such investments, both in terms of capital and in lost revenue from oil production during conversion, mean that other improved oil recovery methods (such as miscible gas

[42] Hustad, C. W., and Austell, J. M., 2004. Mechanisms and incentives to promote the use and storage of CO_2 in the North Sea. *European Energy Law Report I, Intersentia*, 355-380.

[43] Cavanagh, A., and Ringrose, P., 2014. Improving Oil Recovery and Enabling CCS: A Comparison of Offshore Gas-recycling in Europe to CCUS in North America. *Energy Procedia,* 63, 7677-7684.

[44] E.g., Melzer, L. S., 2012. Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery (http://neori.org/Melzer_CO2EOR_CCUS_Feb2012.pdf).

injection) are likely to remain the preferred option until new tax or funding incentives are applied.

5. Regulatory barriers: There are currently no regulatory barriers to using CO_2 for enhanced recovery, as illustrated by the pilot projects described in section 2.1.2. In many countries, however, it is not possible to combine CO_2-EOR with storage, with the aim to claim emission credits. The European CCS Directive does not explicitly exclude such a combination, but many European Member States have implemented the Directive into more stringent regulations, preventing a CO_2-EOR operation to be part of a CCS project.

It should be noted that where CO_2 is used for EOR, all the acquired CO_2 is ultimately stored, since produced CO_2 is recycled and re-injected both due to its economic value to the project (a business driver) and the objective of ensuring CO_2 storage (an environmental driver). This results in a decreasing demand for CO_2 during the EOR project. This practice is routine in the onshore CO_2-EOR sector in the United States, and exemplified by the large-scale CO_2-EOR and storage projects at Weyburn, Canada.[45]

2.3 Opportunities and recommendations for overcoming barriers

The major barrier to the development of offshore storage or EOR is the lack of progress with large-scale CO_2 capture projects. To resolve this situation, the development of all elements of the capture, transport and storage (or EOR) chain should be supported simultaneously. Nevertheless, the following sections highlight opportunities and recommendations that apply to transport and storage (or EOR).

2.3.1 Offshore CO_2 storage

As mentioned above, there are no significant technical barriers to offshore CO_2 storage. The barriers identified are in the areas of availability of storage capacity and of national regulations.

The high risks and long lead time involved in proving up storage capacity suggest that this could be a governmental task, especially to support the development of first-wave or even second-wave CCS projects. The long lead time (in the range of 7–10 years) means that storage qualification defines the start-up time of a CCS project. Although the unit cost of storage are lower than that of capture, one ‘dry’ hole (i.e., into a formation that proves not to be good store) would significantly increase the cost of storage. It would help prospective CCS stakeholders if governments were to provide a number of pre-qualified storage locations. For such locations, all preparatory work, including the documents for a storage permit application should be made available to reduce the uncertainty regarding the availability of storage. This would support both the storage and the transport elements of CCS projects.

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[45] Aarnes JE, Wildgust N., 2012. Industry experience with large-scale CCS and similar operations. In: Hitchon, B. (Editor), *Best Practices for Validating CO_2 Geological Storage,* Geoscience Publishing, 1-7.

There could also be a role for national authorities in the development of a transport infrastructure. During the pilot and demonstration phase of CCS, separate CO_2 volumes will be relatively small. These projects could be developing the first elements of the large-scale infrastructure, if sufficient incentive is given to oversize the transport infrastructural elements. Especially during the early phase of CCS, public-private partnership is essential to generate these large infrastructural works.

An increase in the available financial incentives for (offshore) CCS project is needed to increase the speed of development of offshore CCS. Funding mechanisms should consider funding operational costs, as well as up-front investments. The CO_2 emission tax in Norway and the contract-for-difference in the UK are examples of funding mechanisms that provide certainty of funding during the lifetime of a CCS project, whether it is a demonstration or full-scale project.

2.3.2 Offshore CO_2-EOR

For offshore CO_2-EOR a number of barriers in the technical domain were identified, in contrast with offshore storage.

Current CO_2-EOR techniques, such as those used in Texas, are aimed at minimizing the volume of CO_2 stored in the oilfield and maximizing the volume of CO_2 that is circulated. This minimizes the volume of CO_2 purchased. If there is an economic benefit in storing the CO_2, for example through emission credits that can be claimed for the CO_2 stored, EOR techniques can optimized not only for enhanced oil production, but also for the stored CO_2 volume.[46] This would improve the value of CO_2-EOR operations when they form part of a capture-transport-storage project.

One of the barriers reported widely for CO_2-EOR projects is the investment required for the modification of platform and installations, and the lost revenue during modification. By moving equipment required to separate and condition the CO_2 to the seafloor, modifications to the platform can be minimized. Recent development of subsea processing offers an increasing number of new concepts and opportunities.[47] Such processing can also be applied for treating well streams resulting from CO_2 flooded offshore reservoirs. Subsea processing systems and equipment such as separators, heat exchangers and pumps have been qualified and are in use in a subsea environment today. During 2015 a subsea compressor48 cc) will be put in commercial operation on the Åsgard field on the Norwegian Continental Shelf. Such a subsea compressor unit might be a key component in an arrangement for treating a CO_2 rich well stream. By exploiting the opportunities the subsea process systems offer, it can be technically feasible to arrange a subsea based well stream process train, which could provide separation of the high concentration CO_2 well stream and reinject the compressed or liquefied CO_2 to the reservoir or into a nearby aquifer. Alternatively the compressed CO_2 could be pumped to an adjacent oil reservoir for CO_2 flooding. However, a

[46] NETL, CO_2-EOR offshore resource assessment, 2014.

[47] Moraes, C., da Silva, F., Monteiro, A. and Oliveira, L.P.: "Subsea versus Topside Processing – Conventional and New Technologies". OTC 24519, 2013; Marjohan, R.: How to increase Recovery of Hydrocarbons Utilizing Subsea Processing Technology" OTC 24934, 2014

[48] OTC-25464-MS, 22411-MS OTC Conference Paper – 2011

complete stabilization of the oil phase at the seabed is not seen as commercially realistic, so some residual CO_2 will follow the treated well stream to the topsides facilities.

Dependent on reservoir conditions, infrastructure available on the topside and requirements to the oil and gas produced on the topsides, the subsea processing solution can be arranged in various ways. One alternative that is seen as technically feasible is to install a gas separation unit where a bulk separation of CO_2 is provided by e.g., selective membranes or other separation concepts. This concept ensures the highest possible degree of extracting commercially recoverable resources from the reservoir.

Another promising aspect of the subsea processing concept is that such arrangements are made with retrievable modules due to the need for inspection and maintenance. Since a typical EOR project has a relatively short life time, most of the subsea processing equipment can probably be reused in new projects. This would offer a commercially better solution as well.

In a final production stage of the reservoir, after the technically and commercially available hydrocarbon resources are extracted, the infrastructure of the subsea facilities can be used for permanent injection of CO_2, hence represent a considerable enabler for CCS.

Recent advances in subsea separation and processing could extend the current level of utilization of sea bottom equipment[49] to also include the handling of CO_2 streams. By moving equipment required to separate and condition the CO_2 to the seafloor, modifications to the platform can be minimized.

In the regulatory domain, an opportunity that has received attention recently is to enable CO_2-EOR projects to benefit from emission credits. The ability to combine enhanced production and storage activities would provide another incentive to utilize the potential for CO_2 storage in oilfields[50] as a driver for the development of CCS. The additional benefit of enhanced recovery could help finance the capture and transport part of the CCS project. This would probably require the EOR operator to perform more and more detailed monitoring, but the MMV technology is available and the additional cost will not significantly increase the overall cost of the EOR operations.

Further opportunities to support the development of offshore CO_2-EOR are to found in what could perhaps be termed the organizational domain.

Although CO_2-EOR is performed on a large scale in Texas, there is only one offshore project in operation and that is the Lula project in Brazil. The startup of new projects could be supported through small late-life oilfields (or a section of larger oilfields) where CO_2-EOR is developed in a demonstration project setting. These small projects could serve as stepping stones to larger-scale projects.

As mentioned above, early CO_2 capture projects are likely to produce limited volumes of CO_2. Each of these projects would not produce the CO_2 required by a single CO_2-EOR oilfield. The CO_2

[49] E.g., http://www.offshore-mag.com/content/dam/offshore/print-articles/volume-74/03/SubseaBoosting.pdf.
[50] IEAGHG, 2009.

demand curve of a typical EOR operation decreases after a peak at the start, which renders the construction of a dedicated pipeline to the field difficult. Ship transport could provide the flexibility that is required in such cases.[51] A small number of ships could link emerging capture projects to pilot and demonstration scale offshore CO_2-EOR operations. This could trigger larger EOR operations, in turn seeding the first elements of offshore CO_2 transport pipelines.

However, while such an approach could help build CO_2 volumes of required size, CO_2-EOR will only be initiated once there is certainty of supply for the typical duration of CO_2-EOR projects. During the startup phase of CCS, demonstration projects may not provide such certainty, unless the commercial phase is very likely to be the next, consecutive step in the development of CCS.

[51] Aspelund et al., 2006. Ship transport of CO_2, *Chem. Eng. Research and Design,* 84, 847-855.

3 Offshore CO_2 Storage and Enhanced Oil Recovery Resource Assessments

3.1 Status of Resource Assessments

The geologic aspects of capacity assessment are the same offshore as onshore, and future global assessment of offshore storage capacity can leverage the work that has been completed onshore, for example, the CSLF task Force Effort[52] as well as the case studies from the offshore North Sea and Gippsland basins.[53]

The largest storage volumes are found in saline storage units, which are porous sedimentary rocks occupied principally by saline water. By most definitions of storage capacity, horizontal low permeability rock layers that serve as confining systems that limit vertical migration of fluids must be identified. The second major storage subcategory is depleted hydrocarbon fields, where hydrocarbons that have been extracted have been partly replaced by injected CO_2. Depleted hydrocarbon fields can be used for storage with no intention of resource recovery, or storage can be linked to EOR or enhanced gas recovery (EGR), in which case it is classified as CCUS. Storage focused on a mineral trapping mechanism has been proposed where the rocks are highly reactive to CO_2. The major reactive rock in sub-sea settings is basalt.

Within each category, the first stage of calculating capacity is to determine the areas to be used. This determination may require defining a confining system or seal for containment in order to define a storage unit or identify areas that have structural traps (for example Brennan et al, 2010,[54] Bentham et al., 2014[55]). Another consideration is the distance between source and sink, with storage volumes distant from sources being disqualified.[56] The assessment of storage in China provides many additional variables for consideration as described by Li (2014)[57] and Jian (2014).[58]

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[52] CSLF, 2008, Comparison between Methodologies Recommended for Estimation of CO_2 Storage Capacity in Geological Media. Carbon Sequestration Leadership Forum (CSLF), Bachu, S. (Ed.)

[53] Gibson-Poole, Catherine M.; Svendsen, L. Underschultz, J. Watson, M. Ennis-King, J. P. van Ruth, P., Nelson, E., Daniel, R. and Cinar, Y., 2006, Gippsland Basin geosequestration: a potential solution for the Latrobe Valley brown coal CO_2 emissions, APPEA Journal

[54] Brennan, S.T, Burruss, R.C., Merrill, M.C., Freeman, P.A., and Ruppert, L.F., 2010, A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage, United States Geological Survey open file report 2010-1127 http://pubs.usgs.gov/of/2010/1127/ofr2010-1127.pdf

[55] Bentham, M., Mallows, T., Lowndes, J., and Green, A. (2014). CO_2 STORage Evaluation Database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia*, *63*, 5103-5113.

[56] Bachu, S., Bonijoy, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N.P., Mathiassen, O.M., 2007. CO_2 storage capacity estimation: methodology and gaps. International Journal of Greenhouse Gas Control,1, 430–443.

[57] Li, Jian, 2014, The capacity building in carbon dioxide capture and storage in China, China Australia Geological Storage workshop, CO_2 storage capacity assessment and demonstration in China, completed 2014, China Geological Survey

[58] Jian, Xiaofeng, 2014, CO_2 Geological Storage of Target Area Scale Selection and Evaluation Method, China Australia Geological Storage workshop,http://www.cagsinfo.net/pdfs/cags2-workshop3/2.1_CO2_Geological_Storage_of_Target_Area_Scale_Selection_and_Evaluation_Method.pdf

Once the storage areas to be quantified have been defined, the mass of CO_2 that can be stored in that volume is assessed by determining the fraction of the volume that can be used, and the density of the CO_2 to be stored in that volume. Quantification of capacity depends on the definition of storage adopted. Some methods are static and based an assessment of pore volume multiplied by an efficiency factor (e.g., NETL, 2012[59]). Other capacity estimations, for example the Enhanced Analytical Simulation tool (EASiTool),[60] are based on the rate at which CO_2 can be added to the system without exceeding a pressure limit. Several studies have compared capacity methods and found that the assumptions create large variation in storage capacity assessments, however these variations resolve toward similar order-of-magnitude calculations.[61,62,63]

3.1.1 Saline

The global distribution of saline storage at the coarsest level can be assessed by evaluating thickness of sedimentary cover. This method was used for the initial onshore U.S. capacity assessment[64] and is used in this report for the initial assessment of global subsea storage (Figure 3-1). Certainly not all of the volume plotted in Figure 3-1 is useable, because the existence of both reservoir and confining system must be demonstrated, however the thick areas can be considered prospective.

3.1.2 Storage related to oil and gas production

While significant experience exists in CO_2-EOR, that experience is unevenly distributed globally, with the majority occurring in the United States (specifically West Texas, since 1972). The majority of that experience is onshore due to the favorable economics in the current environment. However, the eventual development of offshore CO_2-EOR is anticipated, although it is difficult to predict when market pressures will make those projects economic. Likely the development will be incremental where projects have highest chance of success and return on investment. In addition, government financial incentives may accelerate deployment.

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[59] NETL, 2012. The United States 2012 Carbon Utilization and Storage Atlas, 4th ed. U.S. Department of Energy – National Energy Technology Laboratory – Office of Fossil Energyhttp://www.netl.doe.gov/technologies/carbon seq/refshelf/atlas/

[60] Hossieni S. A., Kim, Seunghee, and Zeidouni, Mehdi, 2014, Application of multi-well analytical models to maximize geological CO_2 storage in brine formations. Energy Procedia 63 p. 3563-3567.

[61] Szulczewski, M.L., MacMinn, C.W. Herzog, H.J., and. *Juanes, R.,* 2012, *Lifetime of Carbon Capture and Storage as a Climate-change Mitigation Technology*, Proceedings of the National Academy of Sciences, Vol 109:14, pp 5185-5189www.pnas.org/cgi/doi/10.1073/pnas.1115347109

[62] Goodman, Angela, Bromhal G., Strazisar, B., Gutherie, W. F., Allen D., 2013, Comparison of methods for geologic storage of carbon dioxide in saline formations, International Journal of Greenhouse Gas Control, v. 18, p. 329-342.

[63] Wallace, Kerstin, 2013, Use of 3-dimensional dynamic modeling of CO_2 injection for comparison to regional static capacity assessments of Miocene sandstone reservoirs in the Texas State Waters, Gulf of Mexico, University of Texas master's thesis.

[64] Bergman, M., Winter, E.M., 1995. Disposal of carbon dioxide in aquifers in the U.S. Energy Conversion and Management, v. 36, p. 523–526.

Research to facilitate CO_2-EOR focuses on improving recovery rates and reducing the costs per barrel produced. The conformance (sweep efficiency) of the floods is a primary factor governing these and miscibility, multi-phase flow, wettability, and engineered mobility (i.e., nanoparticles) are also important.

While there has been extensive offshore exploration for hydrocarbons since the 1960s in many basins throughout the world (and exploration continues with success), the opportunities for enhanced oil recovery using CO_2 are less well known. This is in part due to resource development which favors onshore enhanced oil recovery as more economic at this time. However, there are places where CO_2 is actively being used or considered to enhance offshore hydrocarbon production. The most notable of these are in the offshore of Brazil and Malaysia.

In the offshore of southeastern Brazil, exploration of the deep (pre-salt) reservoirs in the Campos and Santos Basins has indicated many of the gas reservoirs are high in CO_2 content (perhaps 10-20 percent), complicating logistics and development plans. Petrobras has repeatedly indicated it prefers not to vent the naturally produced CO_2 if it can be separated economically in the offshore environments (as is done by Statoil in the North Sea at the Sleipner development). The preferred utilization of CO_2, providing the technical challenges of deep reservoirs in heterogeneous carbonate rocks can be overcome, is to inject the CO_2 into producing hydrocarbon fields (e.g., Lula, which is currently active at ≈700 kt CO_2 per year) for enhanced recovery. There are over 35 fields in the Campos Basin that are mature and could benefit from enhanced oil recovery (e.g., Ketzer et al., 2007[65]; Almeida et al., 2010[66]; Rockett et al., 2013[67]).

In Malaysia (Sarawak), the enormous Petronas K5 Project in the southern South China Sea will produce natural gas with up to 70 percent carbon dioxide. In the region there are estimates of more than a dozen similar scale fields with similar CO_2 content. These fields hold perhaps 13 trillion cubic feet of natural gas (methane) and twice as much carbon dioxide. For perspective, this is equivalent to current national volumetric emissions of CO_2 for some countries. The concept being pursued is to boost production in depleting nearby offshore oilfields. FEED studies are anticipated to start in 2015. An additional pilot project was considered for the Dulang offshore oilfield.[68]

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[65] Ketzer, J. M., Villwock, J. A., Caporale, G., da Rocha, L. H., Rockett, G., Braum, H., and Giraffa, L., 2007, Opportunities for CO_2 capture and geological storage in Brazil: The CARBMAP Project. In Sixth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania.

[66] Almeida, A. S., Lima, S. T. C., Rocha, P. S., Andrade, A. M. T., Branco, C. C. M., Pinto, C., and Carlos, A., 2010, January). CCGS opportunities in the Santos basin pre-salt development. In SPE International Conference on Health Safety and Environment in Oil and Gas Exploration and Production. Society of Petroleum Engineers.

[67] Rockett, G. C., Ketzer, J. M. M., Ramírez, A., and van den Broek, M. (2013). CO_2 Storage Capacity of Campos Basin's Oil Fields, Brazil. Energy Procedia, 37, 5124-5133

[68] Wilson and Hall, 2010, Tectonic influences on SE Asian carbonate systems and their reservoir development. *Cenozoic Carbonate Systems of Australasia: SEPM, Special Publication*, *95*, 13-40.

In the Gulf of Mexico, offshore EOR is not active, but anticipated.[69] Economic reasons for delayed deployment (as for most basins) include transport expense, offshore processing/compression, and higher well and facilities operations costs. Estimates of stranded oil from primary production are significant, perhaps as much as 27 billion barrels.[70] Of this, perhaps 6 billion may be recoverable using CO_2-EOR techniques. Given the royalty structure in the US offshore, the Federal government has incentive to facilitate EOR, and would also be the long-term steward for CO_2 storage projects. The Gulf of Mexico is the largest market for infrastructure decommissioning, and there is a time-sensitive motivation for re-commissioning those facilities for CO_2 injection, and thus delay expensive decommissioning processes. In the 1970s, CO_2-EOR was investigated in the Gulf of Mexico at Weeks Island, Iberia Parish, Louisiana.[71] While the location was not technically 'offshore', it was in a bay setting near the coastline in the same geological formations that are most prospective in the near offshore. Estimates of oil recovery from CO_2 injection were estimated at 26 MMBO for similar depleted reservoirs in the region. The project injected 50,000 tons of CO_2, and the extent of subsurface migration was successfully monitored with neutron well logging.

Other offshore investigations for CO_2-EOR have been performed for the North Sea (Heidrun-Draugen; Don Valley), Abu Dhabi (Persian Gulf), Vietnam (Rang Dong), and the South China Sea (SCS; Pearl River Mouth Basin; Huizhou 21-1 Field). In general, the SCS opportunities are similar in technical aspects and original recovery percentages to the North Sea Basin, Gulf of Mexico, and Brazil, although the field sizes for SCS are somewhat smaller. All basins have similar infrastructure needs, although the distances offshore vary. SCS has favorable light oil compositions (low density and viscosity), relatively high porosity and permeability, and shallow water depths.

3.1.3 Storage in subsea basalts

Development of mineral storage in subsea basaltic (mafic and ultramafic) rocks is at an early stage dominated by conceptual studies. Three complementary CO_2 trapping mechanisms are proposed. Most research focuses on trapping by reaction of dissolved CO_2 with the abundant divalent cations (Ca^{2+}, $Mg^{2+}$and Fe^{2+}) in these rocks through a naturally accelerated weathering reaction and

[69] DiPietro, J. P., Kuuskraa, V., and Malone, T. (2014). Taking CO_2 Enhanced Oil Recovery to the Offshore Gulf of Mexico: A Screening-Level Assessment of the Technically and Economically-Recoverable Resource. *SPE Economics and Management*, (Preprint).

[70] Koperna, G. J., and Ferguson, R. C. (2011, January). Linking CO_2-EOR and CO_2 Storage in the Offshore Gulf of Mexico. In *Offshore Technology Conference*. Offshore Technology Conference.Gislason S.R. and Oelkers, E.H., 2014, Carbon Storage in Basalt, Science 344, p. 373-374 doi10.1126/science.1250828

[71] Shell Oil Company, 1980, Weeks Island 'S' sand reservoir B gravity stable miscible CO_2 displacement, Iberia Parish, Louisiana, U.S. Department of Energy contract #EF-77-C-05-5232, Third Annual Report, National Petroleum Technology Office, Tulsa, OK.

subsequent precipitation as the minerals such as calcite, magnesite, and siderite.[72,73,74] Structural trapping in porous zones within the basaltic rocks beneath impermeable seals (either impermeable basalts or other impermeable strata such as mudrocks) and density trapping where injected CO_2 is more dense than seawater are also considered.[75] Testing of storage by mineralization has been conducted fairly extensively in laboratories and in three on-land field settings.[76,77,73,78] CO_2 can be dissolved in water prior to injection as is done in the CARBFix experiment in Iceland and the Lamont-Doherty Earth Observatory experiment in the Palisades sill, NY, or injected as a separate phase as has been done the Big Sky experiment in Wallula, Washington.[79]

The distribution and amount of usable storage in oceanic basalt is poorly constrained. Ocean basins typically contain kilometers of basaltic crust with various fabrics and compositions. [80] Consideration of storage in basalt may provide options for areas where porous media storage is limited, for example in the Pacific Northwest of the United States.[81] Limitations of utilization of basalt for storage have not been systematically assessed but may include excessive water depth, excessive distance from on-land CO_2 point sources, excessive depth of burial beneath sediments, and limiting properties of the basaltic rocks such as presence of porosity and a functional top seal.

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[72] Lackner, K.S., Wendt, C. H., Butt, D.P., Joyce, E.L., and Sharp, D.H., 1995. Carbon dioxide disposal in carbonate minerals: Energy, v.20, p.1153–1170.

[73] Gislason, S.R., and Oelkers, E.H., 2014. Carbon storage in basalt. Science, v. 344, no. 6182, pp. 373–374.

[74] Brown, Gordon E. et al. 2009, Geological sequestration of CO_2: mechanisms and kinetics of CO_2 reactions in mafic and ultramafic rock formations. GCEP Progress report, 27 p.
http://web.stanford.edu/~gebjr/09%20GCEP%20Progress%20Report%20%28Brown%20et%20al.2%29.pdf

[75] Marieni, Chiara, Henstock, T. J., and Teagle, D. A. H., 2013, Geological storage of CO_2 within the oceanic crust by gravitational trapping, Geophysical research Leters, v. 40, p. 6219-6224 doi:10.1002/2013GL058220, 2013.

[76] Matter, J. M., and Takahashi, Taro, and Goldberg, David, 2007, Experimental evaluation of in situ CO_2 –rock-water reactions during CO_2 injection in basaltic rocks: implications for geological CO_2 sequestration. G3 Geochemistry Geophysics Geosystems, v. 8, doi:10.1029/2006GC001427

[77] Snæbjörnsdóttir, Sandra Ó. Wiese, Frauke, Fridriksson, Thrainn, Ármansson, Halldór, Einarsson, Gunnlaugur M., Gislason, Sigurdur, R., 2013, CO_2 storage potential of basaltic rocks in Iceland and the oceanic ridges, GHGT-12, Energy Procedia, https://zenodo.org/record/12869/files/Snbjornsdottir_et_al._GHGT-12_storage_potential_2014.pdf

[78] McGrail, B.P., Spane, F.A., Amonette, J.E., Thompson, C. R., and Brown, C. F., 2014, Injection and monitoring at the Wallula basalt project, GHGT 12, Energy Procedia, (2014) 2939-2948.

[79] Big Sky Carbon Sequestration Partnership (accessed 2015) Phase II Basalt Injection Phase http://www.bigskyco2.org/research/geologic/basaltproject

[80] Wright, John and Rothery, David, 1998, The ocean basins: their structure and evolution, 2nd edition, Oxford, UK, 185 p.

[81] Goldberg, D. S., Takahashi, T., and Slagle, A. L. (2008). Carbon dioxide sequestration in deep-sea basalt. *Proceedings of the National Academy of Sciences*, *105*(29), 9920-9925. Lackner, K.S., Wendt, C.H., Butt, D.P., joyce, E.L., and Sharp, D. H., 1995, Carbon dioxide disposal in carbonate minerals, Energy v. 20, p. 1153-1170 Elsevier.

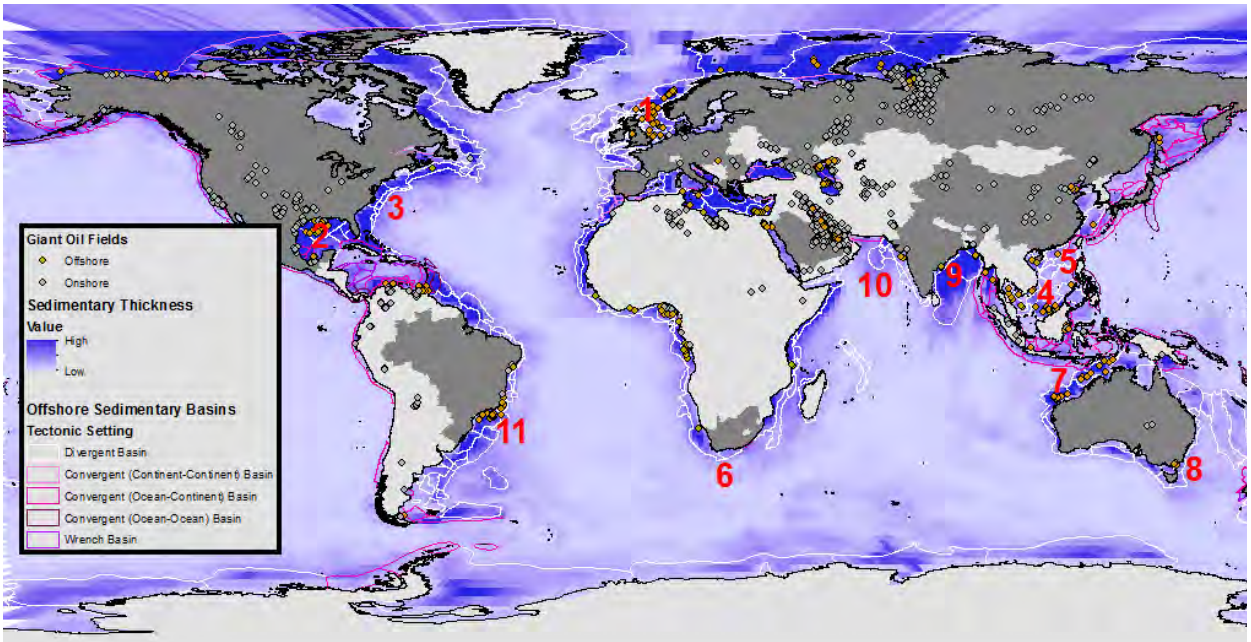

Figure 3-1. Thickness of sedimentary cover in offshore areas based on data from Divins (2003). CSLF countries are shaded. Numbers correspond to table 3-1 and to the detailed discussions in following texts. Basin outlines from AAPG (2013),[82] and supergiant hydrocarbon fields from Mann et al. (2003).[83]

More data are needed about how to assess injectivity and sealing capacity and the impact of mineralization storage processes on these key functions prior to fully understanding the distribution of suitable storage sites. Parts of the seafloor are tectonically active which may limit potential for storage in some areas. Maps of sub-sea distribution of selected basalts are presented by Brown et.al. (2009)[74] and Big Sky Carbon Sequestration Partnership[79], however maturation of the concept is needed to improve assessment of the potential global contribution of this method.

3.1.4 Status of global storage capacity assessment in subsea basins

To provide more information on the status of assessment of capacity in subsea basins globally, eleven prospective basins from Figure 3-1 were selected and a literature review conducted (Table 3-1). Status is highly variable. The best known basin is the North Sea for which a numerous regional and site-specific studies specifically targeted to assess storage have been completed and

[82] AAPG, 2013, Robertson Tellus Sedimentary Basins of the World Map, http://www.datapages.com/Brody, S.D., Grover, H., Bernhardt, S., Tang, Z., Whitaker, B., and Spence, C., 2006, Identifying potential conflict associated with oil and gas exploration in Texas State coastal waters: A multi-criteria approach, Environmental Management, 38: 597-617.

[83] Mann, P., Gahagan, L., and Gordon, M. B. (2003). Tectonic setting of the world's giant oil and gas fields, p 15-105.

published. Other basins have significant data available about basin geology but have only a few or no studies of the suitability of the basins for geologic storage. Basins are numbered in the text, Figure 3-1 and Table 3-1.

3.1.4.1 North Sea Basin (1)

The North Sea Basin (NSB) is one of the most explored marine basins in the world, with decades of subsurface exploration summarized in the literature.[84,85] The first and longest running CO_2 storage project in the world has occurred at the Sleipner Field in the North Sea. The potential (capacity) for CO_2 sequestration is fairly well defined in regional geologic atlas format (both for the Norwegian and UK sectors of the central North Sea).[86,87,85] The storage capacity in the Norwegian sector has been estimated to have over 45 Gt of CO_2 storage, predominantly in the Utsira, Skade, Bryne, and Sandnes Formations. The UK sector of the North Sea has similar capacity. The southernmost NSB has thinner Cenozoic deposition, resulting in generally less storage capacity.[88]

Many passive continental margins initiated as rift basins during continental separation, with continued separation forming two separate shelves on opposite sides of an ocean. The North Sea Basin had a somewhat unique evolution in that rifting stalled prior to full development. This resulted in two important aspects for CO_2 storage. The first is that the basin depocenter remained in the middle of the basin (farthest from the coastline), where thick sequences of clastic sediment accumulated.[89] The second is that during this time, the basin experienced glacial advance and retreat that resulted in cyclical vertical tectonics, which is atypical for many passive margin settings (although perhaps somewhat similar to the northern Atlantic margin of the United States). These vertical isostatic basin elevation changes have caused the basin to experience dynamic cycles in pore pressure, such that the recent glacial history may be a significant influence in the structure, seal quality, and fluid history of the basin. Understanding the impact that these aspects may have for CO_2 storage is actively being pursued with the recent submission of a research proposal to the Integrated Ocean Discovery Program by an international consortium to drill a series

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[84] Chadwick, R. A., Arts, R., and Eiken, O. (2005). 4D seismic quantification of a growing CO2 plume at Sleipner, North Sea. In *Geological Society, London, Petroleum Geology Conference series* (Vol. 6, pp. 1385-1399). Geological Society of London.

[85] Bentham, M., Mallows, T., Lowndes, J., and Green, A. (2014). CO_2 STORage Evaluation Database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia*, *63*, 5103-5113.

[86] Gammer, D., Green, A., Holloway, S., and Smith, G. (2011). The Energy Technologies Institute's UK CO2 storage appraisal project (UKSAP).

[87] Halland, E. K., Gjeldvik, I. T., Johansen, W. T., Magnus, C., Meling, I. M., Pedersen, S., and Tappel, I. (20112013). CO_2 Storage Atlas: Norwegian North Sea. *Norwegian Petroleum Directorate, PO Box*, *600*.

[88] Nilsen, H. M., Lie, K.-A., Andersen, O., 2015, Analysis of CO_2 trapping capacities and long-term migration for geological formations in the Norwegian North Sea using MRST-CO_2lab; Computers and Geosciences Volume 79, Pages 15-26.

[89] Sclater, J. G., and Christie, P. (1980). Continental stretching: An explanation of the post-mid-cretaceous subsidence of the central North Sea basin. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *85*(B7), 3711-3739.

of wells focusing on the Cenozoic central basin fill to evaluate both the glacial stratigraphy as well as the seal characteristics. In this way, the NSB remains at the global forefront of understanding offshore basins for CCS.

3.1.4.2 Gulf of Mexico Basin (2)

Decades of exploration for hydrocarbons has provided insights into geology of the offshore portion of the Gulf of Mexico Basin.[90]. Most hydrocarbon production and concomitant data are from the northern, western and southern offshore areas of the basin. The Gulf of Mexico was formed during the Mesozoic, and accumulated a thick Jurassic sequence of shale that is important in later tectonics. The Mesozoic section contains significant carbonate with some siliciclastic depositional thickness,[91] however the most significant sediment thickness for CCS purposes are of Oligocene, Miocene and early Pliocene age.[92,93] Thick, coarse-grained clastic units provide storage reservoirs that alternate with laterally-extensive fine-grained units that serve as confining systems. Thin-skinned salt tectonics control the development of structural elements of the northwestern Gulf[94] and various structural configurations have resulted in traps that have accumulated large hydrocarbon volumes through geologic time. Such traps may also be prospective for retaining injected volumes of anthropogenic CO_2.

[90] Seni, S. J., T. F. Hentz, W. R. Kaiser, and E. G. Wermund Jr. (1997), *Atlas of Northern Gulf of Mexico Gas and Oil Reservoirs*, 199 pp., The University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

[91] Winker, C. D., and R. T. Buffler (1988), Paleogeographic evolution of early deep-water Gulf-of-Mexico and margins , Jurassic to Middle Cretaceous (Comanchean), *AAPG Bulletin-American Association of Petroleum Geologists*, *72*(3), 318-346.

[92] Galloway, W. E. (2009), Giant Fields North America: Gulf of Mexico, in *GEO ExPro - Geoscience and Technology Explained*, edited, London, UK.

[93] Galloway, W. E., P. E. Ganey-Curry, X. Li, and R. T. Buffler (2000), Cenozoic depositional history of the Gulf of Mexico basin, *AAPG Bulletin*, *84*(11), 1743-1774.

[94] Diegel, F. A., J. F. Karlo, D. C. Schuster, R. C. Shoup, and P. R. Tauvers (1995), Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin, in *Salt Tectonics; A Global Perspective*, edited by M. P. A. Jackson, D. G. Roberts and S. Snelson, pp. 109-151, American Association of Petroleum Geologists.

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One focus of CCS research has been on the northern and northwestern margins of the basin.[95,96,97,98,99,100] This area is considered prospective because of the proximity of high quality storage potential, large industrial sources, extensive development of hydrocarbon resource, and demonstrated onshore EOR potential. Extensive geologic datasets from hydrocarbon exploration allow for informed regional geologic assessments. In conjunction with newer, higher-resolution technology detailed static geologic models can be generated that can then utilize hydrocarbon production histories to generate well-constrained flow simulation models of future anthropogenic CO_2 injection sites.

Research has only recently begun on evaluating offshore basins of the southern Gulf of Mexico in Mexican waters, which like the northern Gulf, are well known because of extensive hydrocarbon development.[101]

3.1.4.3 Atlantic Coast of United States (3)

The formation of the central North Atlantic Ocean began with continental rifting (separation of North America and Africa) in late Triassic to early Jurassic time followed by seafloor spreading throughout the rest of the Mesozoic and into the Cenozoic. Offshore from the East Coast of the United States, rift basins and grabens that formed during this continental breakup were subsequently filled with great thicknesses of sediment eroded from the present day Appalachian Mountains. This type of passive continental margin is known throughout the world as an Atlantic-type continental margin.[102] Major basins of interest off the Atlantic coast of eastern United States are, from north to south, the Georges Bank Basin (GBB), Baltimore Canyon Trough (BCT), Carolina Trough (CT), South Georgia Basin (SGB), the Blake Plateau Basin (BPB), and the

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[95] Mickler, P. J., C. Yang, J. Lu, and K. D. Lankford (2014), Laboratory Batch Experiments and Geochemical Modelling of Water-rock-super Critical CO_2 Reactions in Gulf of Mexico Miocene Rocks: Implications for Future CCS Projects, *Energy Procedia*, *63*(0), 5512-5521.

[96] Miller, E. N. (2012), A question of capacity assessing CO_2 sequestration potential in Texas offshore lands, 119 pp, University of Texas at Austin.

[97] Nicholson, A. J. (2012), Empirical Analysis of Fault Seal Capacity for CO_2 Sequestration, Lower Miocene, Texas Gulf Coast, in *Unpublished Masters Thesis*, edited, p. 88, The University of Texas at Austin.

[98] Wallace, K. J. (2013), Use of 3-Dimensional Dynamic Modeling of CO_2 Injection for Comparison to Regional Static Capacity Assessments of Miocene Sandstone Reservoirs in the Texas State Waters, Gulf of Mexico, 152 pp, The University of Texas at Austin, Austin.

[99] Wallace, K. J., T. A. Meckel, D. L. Carr, R. H. Treviño, and C. Yang (2014), Regional CO_2 sequestration capacity assessment for the coastal and offshore Texas Miocene interval, *Greenhouse Gases: Science and Technology*, *4*(1), 53-65.

[100] Yang, C. B., R. H. Trevino, T. W. Zhang, K.D. Romanak, K. Wallace, J. M. Lu, P. J. Mickler, and S. D. Hovorka (2014), Regional Assessment of CO_2-Solubility Trapping Potential: A Case Study of the Coastal and Offshore Texas Miocene Interval, *Environmental Science and Technology*, *48*(14), 8275-8282.

[101] Jacobs, T., 2015, Bringing Enhanced Oil Recovery to Mexican Fields, JPT special issue "Uncovering Mexico", January 2015, pp 54-

[102] Bally, A. W., 1981, Atlantic-type continental margins *in* Bally, A. W., ed. Geology of passive continental margins: American Association of Petroleum Geologists Education Course Notes, series 19, p. 1-48.

Bahamas Basin (BB). Three of these (GBB, BCT, CT) are known as classic Atlantic-type marginal basins.[103]

Complexities of regional tectonics over time have resulted in big differences in geology along the U.S. Atlantic coast, including large variations in width of the continental shelf. As a result, only two of the classic Atlantic basins that are filled with clastic sediment, GBB and BCT, are located within shallower water depths of the U.S. Atlantic continental shelf. These basins have high potential for sub-seabed geologic storage (GS) of CO_2.The BCT has previously been considered for sub-seabed CO_2 GS;[104] however, more work is needed before the CO_2 sub-seabed GS potential of the GBB is known. The SGB, while not being a classic Atlantic-type basin, has thick sequences of clastic sedimentary rock that also have significant potential for CO_2 GS, especially in a section lying offshore from Georgia. A stratigraphic analysis of the SGB and preliminary capacity assessment was completed in 2011.[105]

Reconnaissance-level estimates of capacity for CO_2 GS were completed in 2008 for areas offshore from the Carolinas and landward of the Carolinas Trough.[106] These capacity estimates will need to be revisited because part of the assessed area is off the continental shelf in water up to several kilometers deep. Atlantic coastal areas south of the SGB may be less favorable for sub-seabed GS of CO_2 because they are dominated by carbonate sediments and are more tectonically active. For example, the BPB contains a shear zone that connected eastern Gulf of Mexico and central Atlantic, as well as abundant mafic intrusions. BB has strike-slip, and compressional zones near Caribbean.[107]

Early information on the offshore sub-seabed Atlantic came from hydrocarbon exploration on the continental shelf overlying GBB, BCT, and SGB starting in the late 1970s. Because of opposition from environmental groups, much of the subsequent work (drilling, seismic refraction, and gravity modeling) was completed by scientific expeditions such as JOIDES, DSDP, COST, and USGS.[108] In fact, current drilling moratoria for offshore Atlantic are in effect through 2017.

[103] Grow, J. A. and Sheridan, 1988, U.S. Atlantic continental margin: A typical Atlantic-type or passive continental margin in Sheridan, R. E. and Grow, J. A., eds., The Geology of North America, Volume I-2,The Atlantic Continental Margin: Geological Society of America, p. 1-7.

[104] Midwest Regional Carbon Sequestration Partnership characterization of offshore New Jersey - http://www.mrcsp.org/userdata/phase_II_reports/njgs_carbon_sequestration_report_web.pdf

[105] Smyth, R. C., and Carr, D. L., 2011, Continued evaluation of potential for geologic storage of carbon dioxide in the southeastern United States: UT Austin, BEG unpublished contract report, 39 p.

[106] Smyth, R. C. et al., 2008, Potential sinks for geologic storage of carbon dioxide generated by power plants in North and South Carolina: UT Austin, BEG unpublished contract report, 58p.

[107] Mattick, R. E. and Libby-French, J., 1988, Petroleum geology of the United States Atlantic continental margin in Sheridan, R. E. and Grow, J. A., eds., The Geology of North America, Volume I-2,The Atlantic Continental Margin: Geological Society of America, p. 445-462.

[108] AAPG, 2013, Robertson Tellus Sedimentary Basins of the World Map, http://www.datapages.com/

3.1.4.4 Southeast Asia (4)

The basins to the northeast of Malaysia and Indonesia are different from the more common passive margin extensional basins in that they have a prolonged compressional (convergent) history. This convergence has caused rapid subsidence of thick carbonate stratigraphic sections, causing the generation of prolific gas that has high associated CO_2 contents (Natuna: 70 percent CO_2, 200 Tcf CO_2; Kuala Langsa: 82 percent CO_2, >20 Tcf CO_2). In the North Sumatra Basin, average CO_2 content in the lower Miocene Peutu Formation is around 25 percent, and in the deeper Paleocene Tempur Formation it is typically over 50 percent. It is thought that the rapid subsidence of Cenozoic carbonates and subduction-related volcanism[109,110] generated more CO_2 than could be assimilated through natural processes in the basin (titration during migration; Cathles and Schoell (2007)[111]). Published details suggest that the most common geological circumstances for the occurrence of high concentrations of CO_2 are deep faults close to gas traps, reservoirs close to hot basement and carbonates associated with post-trap igneous activity. The prediction of CO_2 content has a major impact on exploration and production strategies. The ultimate fate of the CO_2 if these large methane accumulations were to be produced is unknown, but reinjection for storage may be guided by understanding the settings and characteristics of natural accumulations.

3.1.4.5 Pearl River Mouth Basin, offshore China (5)

According to Zhou et al. (2011),[112] the Pearl River Mouth Basin (PRMB) is "an extensional basin in the passive continental margin of the northern South China Sea" that was formed during Paleogene rifting of the South China Block and further developed through later (Neogene) subsidence. The basin contains more than 6 km of Cenozoic sediments in its continental shelf portion. The sedimentary section mostly comprises alternating units of sandstone and mudrock (shales, mudstones and siltstones) with some early Miocene limestone (reef) developed on structural highs. Hydrocarbon producing reservoirs are late Oligocene to middle Miocene in age as are potential CO_2 storage reservoirs. The prospective units are deltaic, channel, transgressional, slope and low-stand fan sandstones, and reef and platform carbonates.[112] Similarly, known hydrocarbon top seals are of early to middle Miocene age (within Hanjiang and Zhujiang formations), and they correspond to potential CO_2 confining systems, which can attain net mudstone thicknesses of 400–800 m in the Hanjiang formation.[112] Reservoirs within the Hanjiang and Zhujiang formations exhibit porosities from 16–29 percent and permeabilities from 188–1732

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[109] Wilson and Hall, 2010, Tectonic influences on SE Asian carbonate systems and their reservoir development. Cenozoic Carbonate Systems of Australasia: SEPM, Special Publication, 95, 13-40.

[110] Nayoan, G. A. S., and Arpandi, M. S. (1981). Tertiary carbonate reservoirs in Indonesia.

[111] Cathles, L. M., and Schoell, M. (2007). Modeling CO_2 generation, migration, and titration in sedimentary basins. Geofluids, *7*(4), 441-450.

[112] Zhou, D., Z. X. Zhao, J. Liao, and Z. Sun (2011), A preliminary assessment on CO_2 storage capacity in the Pearl River Mouth Basin offshore Guangdong, China, *International Journal of Greenhouse Gas Control*, *5*(2), 308-317.

mD as reported by Zhou (2011)[112] after Chen et al. (2003).[113] The major carbon geo-sequestration uncertainties in the PRMB are the distribution of reservoirs and confining systems. The PRMB is adjacent to one of the most highly industrialized regions of China (Guangdong Province),[114] where several petrochemical plants have been producing high-concentration CO_2 and where two units in the coal-fired Haifeng power plant are designed to be capture-ready.

3.1.4.6 Offshore storage capacity of South Africa (6)

South Africa's total emission of carbon dioxide is over 400 Mt/y according to estimation in 2010.[115] More than ninety percent of South Africa's electricity is generated from coal.[116] Clean coal technology is vital to South Africa's coal industry in a low carbon future.[117] CCS has been identified as one of the technical approaches to reduce carbon dioxide emissions in government's long-term mitigation plan. South Africa Centre for CCS has prepared a roadmap towards full commercial operation of geological storage of in 2025.

The Atlas on Geological Storage of Carbon Dioxide in South Africa released in 2010 determined that 98 percent of the country's ≈150 Gt storage capacity lies in three offshore Mesozoic basins, the Outeniqua Basin (south coast), Orange Basin (west coast), and Durban and Zululand Basin (east coast) (Figure 3-2). The potential for storage in the depleted oil and gas fields is limited, estimated 62 million tons of CO_2. Total storage capacity of the known oil and gas reserves in the Orange and Outeniqua Basin is estimated 15 million tons of CO_2 after depletion.[118,115] The majority of the estimated storage capacity is from deep saline formations.

In these offshore basins, multiple storage/confining intervals occur in the thick strata of rift-drift sediments. Fluvial marginal-marine and shelf sandstones in the syn-rift sequences and slope/marine fan sandstones in the drift sequences provide storage intervals, while drift and younger deep marine shales provide good confining units. Among them, the Outeniqua Basin is the most explored with existing oil and gas infrastructure, while the Durban/Zululand Basin has

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[113] Chen, C., Shi, H., Xu, S., Chen, X., et al (2003), *Formation Conditions of Tertiary Oil/Gas Reservoirs in Pearl River Mouth Basin (East)*, 266 pp., Beijing.

[114] Bai, B., X. C. Li, Y. P. Yuan, D. Zhou, and P. C. Li (2014), Preliminary assessment of CO_2 transport and storage costs of promising source-sink matching scenarios in Guangdong province, China, *Acta Geotech.*, *9*(1), 115-126.

[115] Viljoen, J.H.A., Stapelberg F.D.J., Cloete, M., 2010, Technical report on the geological storage of carbon dioxide in South Africa. South Africa Council for Geoscience, 238 p. http://www.sacccs.org.za/wp-content/uploads/2011/02/CO2%20Technical%20Report%20on%20the%20geological%20storage%20of%20carbon%20dioxide%20in%20South%20Africa.pdf. Last accessed on February 23, 2015.

[116] South African Department of Environmental Affairs. 2010. National Climate Change Green Paper, 38 p. https://www.environment.gov.za/sites/default/files/legislations/national_climatechnage_response.pdf. Last accessed on February 20, 2015.

[117] Glazewski, J., Gilder, A., Swanepoel, E. 2012. Carbon Capture and Storage (CCS): Towards a regulatory and legal regime in South Africa. Institute of Marine and Environmental Law (IMEL) and African Climate and Development Initiative (ACDI), University of Cape Town, Cape Town. 42 p. http://www.imel.uct.ac.za/usr/law/imel/downloads/CCS_Report.pdf. Last accessed on February 20, 2015.

[118] Cloete, M. 2010. Atlas on geological storage of carbon dioxide in South Africa. Council for Geoscience, Pretoria, South Africa, 60 pp. http://www.sacccs.org.za/wp-content/uploads/2010/11/Atlas.pdf. Last accessed on February 20, 2015.

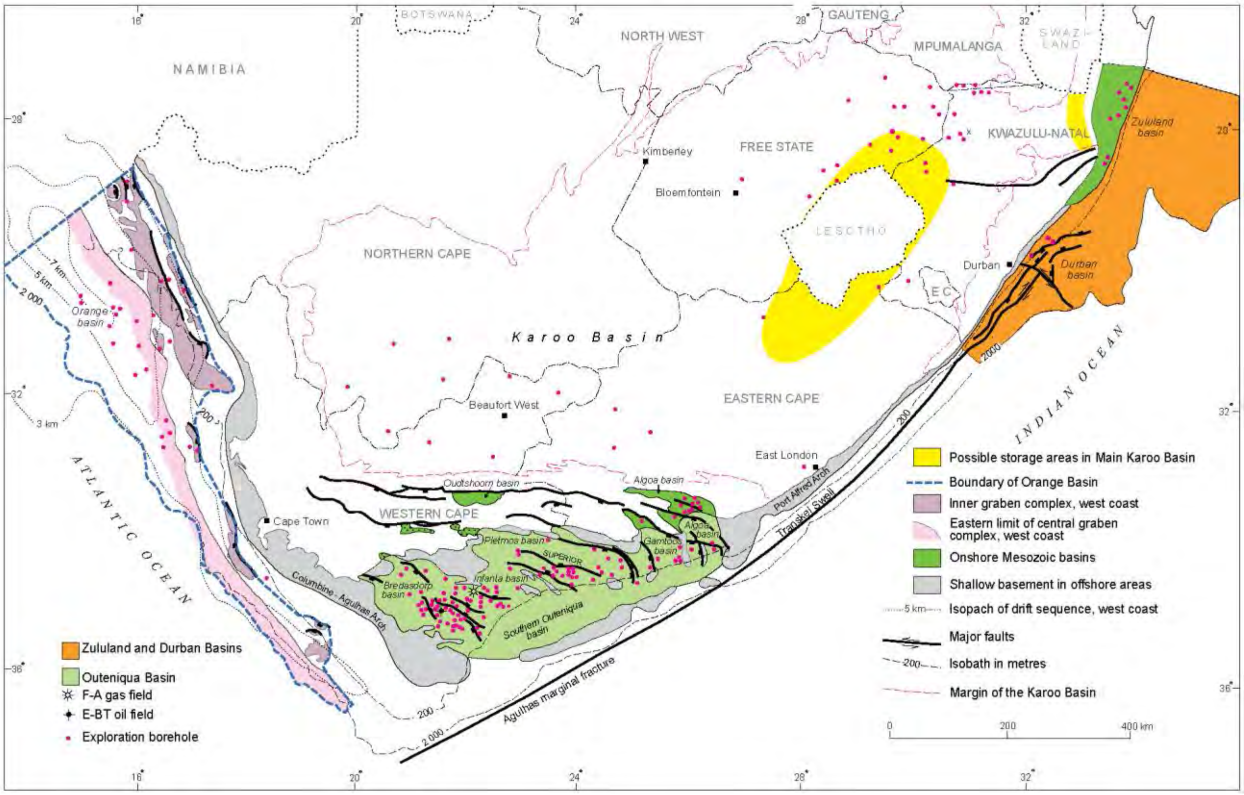

Figure 3-2. Offshore Mesozoic basins along the coast of South Africa[115]

scant data, but is nearest to the major CO_2 sources. The major challenges for carbon geological storage are the overall lack of geological data and the extensive presence of faults and dolerite sills and dykes.

3.1.4.7 NW shelf of Australia (7)

The major continental shelves of North West shelf -Timor Sea area of Australia is underlain by sedimentary basins (e.g., Carnarvoran, Canning, Browse, Bonapart, Yampi) of Australia are in the northwest side of the continent, offshore the state of West Australia. Dense publically accessible seismic data means that this complex stratigraphy is well documented in the public domain as well as in the oil and gas industry (e.g., Longley et al, 2003[119]).

[119] Longley, L. M., Buessenschuett, C., Clydesdale, L., Cubitt, C. J., Davis, R.C., Johnson, M.K., Marshal, N.M., Murray, A. P., Somerville, R., Spry, T. B., and Thompson, N.B., 2003, The North West Shelf of Australia - A Woodside Perspective, AAPG Search and Discovery article #10041 (2003) www.searchanddiscovery.com/documents/longley/

Complex Paleozoic basement stratigraphy (2-6 km) impacts the structure and sedimentology of Neogene—Recent basins. Convergent plate setting, dominated by normal faults.[120]

These areas were recognized early as having high storage potential for CO, but questions arose how this areas, distant from populations centers should be evaluated in terms of global potential, as this volume might be too far to be of pragmatic utility.[121] However, the area is highly productive of gas and the Gorgon Project, storing CO_2 stripped from gas, is under construction by a consortium led by Chevron. Although the separation facility as well as the storage project is located on Barrow Island, the project will provide a demonstration of the storage resource of the region. It also continues the theme of early project related to sequestration of CO_2 stripped from gas prior to sending it to market.

3.1.4.8 Gippsland Basin, eastern Australia (8)

During assessment of the storage resource of Australia, the Gippsland Basin was identified as a favorable target[122,123] One of Australia's hydrocarbon–producing areas, it lies in the near offshore (<100 km to shoreline) of a major brown coal mining and use area in the Latrobe Valley, Victoria, in southeastern Australia.[124] A fault-bounded rift basin with anticlinal structures has undergone a fairly complex evolution from the upper Cretaceous through the Tertiary. The sedimentary basin thickness is >6km,[124] however the characterization for geologic storage has focused on a 400-900 m-thick wedge of Paleocene—Eocene sandstones, shales and coals that form the Latrobe Group.[125] Numerous stacked sandstone reservoirs have mineralogically mature composition sand retain good porosity and permeability. Shale seals of the Lakes Entrance Formation average 395 m thick.[126]

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[120] Keep, Myra and Harrowfield, Mathew, 2008, Elastic flexture and distributed deformation along Australia's North West Shelf: Neogene tectonics of the Bonaparte and Bowse basins. Geological Scarcity of London Special publications, v. 306, p. 185-200.

[121] Bradshaw, John and Rigg, Andy, 2011, The GEODISC Program: Research into Geological Sequestration of CO_2 in Australia Environmental Geosciences, September 2001, v. 8, p. 166-176, doi:10.1046/j.1526-0984.2001.008003166

[122] Bradshaw, John and Rigg, Andy, 2011, The GEODISC Program: Research into Geological Sequestration of CO_2 in Australia Environmental Geosciences, September 2001, v. 8, p. 166-176, doi:10.1046/j.1526-0984.2001.008003166.

[123] Root. R.S., Gibson-Poole, C.M., Lang, S.C., Streit, J. E., Underschultz, J. R., and Ennis-King, J.,2004 Opportunities for geological storage of carbon dioxide in the offshore Gippsland Basin, SE Australia: an example from the upper Latrobe Group. In Boult, P.J., Johns, D.R. and Lang, S.C., (eds) Eastern Australia Basins Symposium II PESA, 367-388.

[124] Rahmanian, V.D., Moore, P. S., Mudge, W.J., Spring, D.E., 1990, Geological Society of London Special Publication, v. 50, p. 525-544

[125] Gibson-Poole, Catherine M.; Svendsen, L. Underschultz, J. Watson, M. Ennis-King, J. P. van Ruth, P., Nelson, E., Daniel, R. and Cinar, Y., 2006a, Gippsland Basin geosequestration: a potential solution for the Latrobe Valley brown coal CO_2 emissions, APPEA Journal

[126] Gibson-Poole, Catherine M.; Svendsen, L. Underschultz, J. Watson, M. Ennis-King, J. P. van Ruth, P., Nelson, E., Daniel, R. and Cinar, Y., 2006b, Regional Characterization of a Major Storage System: Gippsland Basin, Southeast Australia, CO2SC 2006, Berkeley CA.

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Complex basin evolution result in a long, baffled, predicted regional migration path for buoyant CO_2.

Depleted oil reservoirs are considered as the major target, and EOR is not considered economically viable. Because exploration is currently active and production of known reservoirs is predicted to be ongoing for several decades, a plan for injecting in saline formations down-dip of active producers is proposed, so that CO_2 migration into traps will be delayed until the end of production. Faults are identified on 3D seismic and cut through the prospective reservoir intervals of the Eocene Latrobe Formation.[124] Fault reactivation risk has been considered a significant risk which should be mitigated through management.[128,126,125]

Figure 3-3. Geometry of the Bengal and Indus fans. From Woods Hole Oceanographic Institute.[127]

3.1.4.9 Indus (9) and Ganges-Brahmaputra-Meghna (10) Basins

Starting in the late Eocene, the collision of the India Plate with the Eurasian Plate began uplifting continental crust into the Himalaya Mountains that continues today. Weathering and erosion that counteract mountain building forces supply enormous sediment loads to two composite drainage basins along the Indian Margin (Ganges-Brahmaputra and Indus). Both the Ganges-Brahmaputra and Indus rivers drain over 1 million km^2 that supply sediment to enormous fan accumulations in the Bay of Bengal and Arabian Sea respectively (Figure 3-3). Both fan's stratigraphy is generally characterized by turbidity currents through canyon complexes on the marine shelf that eventually deposit channel-levee features along the length of the fan.[129,130] While these fans are kilometers thick at their thickest part (Indus: 9km; Ganges-Brahmaputra: 16km), Eocene and Oligocene mudrocks in the lower third of the sedimentary column are separated by an unconformity from coarser grained

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[127] Woods Hole Oceanographic Institute. (accessed Mar, 2015. http://www.whoi.edu/oceanus/v2/article/images.do?id=2510

[128] Swierczek, E., Backe, G., Holford, S.P., Tehthorey, E., and Michell, A, 2015, 3D seismic analysis of complex faulting patterns above the Snapper Field, Gippsland Basin: Implications for CO_2 storage. Australian Journal of Earth Sciences: and International Geoscience Journal of the Geological Society of Australia, 62:1, 77-94 DOI 10.1080/08120099.2015.978373

[129] Curray, J. R., and Moore, D. G. (1974). Sedimentary and tectonic processes in the Bengal deep-sea fan and geosyncline. In The geology of continental margins (pp. 617-627). Springer Berlin Heidelberg.

[130] Kolla, V., and Coumes, F. (1987). Morphology, internal structure, seismic stratigraphy, and sedimentation of Indus Fan. *AAPG Bulletin*, *71*(6), 650-677.

Miocene and younger rocks with sediment sourced from Himalaya erosion.[131,132] In terms of CCS potential, reservoir candidates include turbidities 10s of meters thick from levee collapse or kilometer scale channels containing coarse infill.

Novel issues to be evaluated in these large active fans are depth and slope stability, as well as source-sink matching.

3.1.4.10 Campos and Santos Basins, offshore Brazil (11)

The most prospective portion of offshore Brazil for CO_2-related activities is in the Campos and Santos Basins in the southeast. The Campos Basin is a primary candidate for CO_2 storage, given its geology and proximity to coastal CO_2 sources. In the Campos Basin, there is significant potential for CO_2 storage (ca. 950Mt) as assessed for 17 oilfields in the basin, and 75 percent of this storage capacity is found in sandstone reservoirs.[133] Static volumetric estimates of storage for the Campos and Santos Basins suggest they may be able to receive 30 and 80 Mt CO_2 (respectively) per year for decades.[134]

3.2 Opportunities and Recommendations

CSLF countries have access to offshore storage. Those settings are predominantly passive margin extensional clastic basins with Cenozoic age fill, representing high porosity and permeability and ductile seals, with broadly similar extensional faults dominant. Storage opportunities are similar in style and quantity/capacity for many countries. While some aspects are unique, geologic and technologic advances undertaken in one area are more likely to be applicable to other countries. It is recommended that a more thorough evaluation of the geologic storage aspects of many basins (i.e., those in Figure 3-1) be pursued. It is also recommended that an increased level of knowledge sharing and discussion be implemented among the international community to outline the potential for international collaboration in offshore storage to overcome challenges such as cost, and building technical expertise.

[131] Clift, P. D., Shimizu, N., Layne, G. D., Blusztajn, J. S., Gaedicke, C., Schlüter, H. U., and Amjad, S. (2001). Development of the Indus Fan and its significance for the erosional history of the Western Himalaya and Karakoram. Geological Society of America Bulletin, 113(8), 1039-1051.

[132] Curray, J. R., Emmel, F. J., and Moore, D. G. (2002). The Bengal Fan: morphology, geometry, stratigraphy, history and processes. Marine and Petroleum Geology, 19(10), 1191-1223.

[133] Rockett, G. C., Ketzer, J. M. M., Ramírez, A., and van den Broek, M. (2013). CO_2 Storage Capacity of Campos Basin's Oil Fields, Brazil. Energy Procedia, 37, 5124-5133.

[134] Ketzer, J. M., Villwock, J. A., Caporale, G., da Rocha, L. H., Rockett, G., Braum, H., and Giraffa, L., 2007, Opportunities for CO_2 capture and geological storage in Brazil: The CARBMAP Project. In Sixth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania.

Table 3-1 Properties of example basins evaluated for this study are summarized

Map Number	Region	Basin	Avg. water depth (m)	Max water depth (m)	Min sediment thickness (km)	Max sediment thickness (km)	Structural type	Structural comparment-alization	Siesmic Risk	Target formation age (my)	Target formation rock type	Target formation depositional system/facies	Target formation heterogeneity	Confining system type	Confining system age (my)	Major confining system risks	Level of information	Major uncertainties for storage target
1	North Sea	North Sea	~100	330	1	2	Extension	Low	Low	Miocene-Pliocene	Sandstone	Basin-restricted marine lowstand deposits	Medium	Clay-rich shale	Upper Pliocene	Faults from isostatic rebound, wells	High	Leakage potential of faults
2	North America	GoM - nearshore	50	1000	2	8	Extension	Medium	Low	3-30	Sandstone	Progradational continental wedge	Medium	shale-sandstone	3-30	Faults & gas chimneys	High	Closed vs. open reservoir systems
3	North America	US East Coast	100	500	1	10	Passive	Medium	Low	65 - 150	Sandstones	Synrift fluvial, deltaic and shallow marine	Medium	shale, shale-sandstone	50-80	Faults, dike and salt domes	Low	Offshore transport distances, migration along faults
4	SE Asia	South China Sea	70	2000	1.4	9.3	Extension	Medium?	Medium	Tertiary	Sandstones and carbonates	Shoreline, delataic, and reef deposits	High	Marine mudstone with interbedde	Lower-Middle Miocene	Normal faults	Low	Offshore transport distances, migration along faults
5	China	Pearl River Mouth Basin	50	2000	6	14	Extension	High	Medium	5-30	Sandstone with reef carbonates on local structural highs	Marine	High	Transgres-sional mudstone	9-16	Lateral extent and fault leakage	Low	Confining system integrity; reservoir quality
6	South Africa	Outenique, Orange, Durban and Zululand	65	2000	1	7	Extension, assymetrical grabens	High	Medium	Cretaceous	Sandstone	Synrift fluvial, deltaic, shallow and deep marine submarine fan	Medium to high	Multiple synrift and transitional shales	Cretaceous	Faults, dyke penetration	Medium to low	Porosity/ permeability, compartmentaliza tion
7	Australia	NW Shelf	100	200	???	10	Extensional	High	Medium?	Cretaceous	Sandstone	Fluvial-deltaic and marginal marine sandstones	High	Anticlines and fault blocks at base of	Cretaceous	Faults and seeps	Medium	Evidence of hydrocarbon seepage along faults
8	Australia	Gippsland	45	70	3.4	2.9	Compressed rift basin	High	Medium	Paleocene-Eocene	Sandstones	Alluvial plain, Coastal plain, shoreface	Medium	Glauconitic, slighlty calcareous, mud-rich sediments	Oligocene	Faulted, but sealing to hydrocarbons	High	Intersection with still-active production (started 1960)
9	India	Ganges-Brahmaputra	500	2500	1	16	Compression	Medium	High?	20	Sandstones	Local Thickening & Uplift of SS	???	Shale-sandstone	10	Faults/Pinch Out	Low	Lack of Info/ Seismicity
10	India	Indus	500	3000	Pinches Out	12	Compression	Medium	High?	21	Sandstones	Turbidite/ Channel SS	???	Carbonate	11	Faults/Eroded Unconformity	Low	Lack of Info/ Seismicity
11	Brazil	Santos and Campos	2100	2400	1	2	Extension	High	Low	Lower Cretatceous	Sandstones	Carbonate microbialites, turbidites	High	Pre-salt	Cretaceous	Faults	High	Deep water and deep stratigraphy; monitoring

4 CO_2 transport for offshore storage

4.1 Introduction

For offshore storage, CO_2 source and sink are rarely co-located, and when they are, typically it is for offshore hydrocarbon production. Cost-efficient and safe solutions are needed in order to realize large scale value chains for CO_2 capture and transport. Similar to capture and storage of CO_2, methods for transporting CO_2 exist, and have been proven to work. Currently, more than 6,800 km of CO_2 pipelines have been constructed world-wide, most of these are onshore in North America. Small volumes of food grade CO_2 are also transported by ship and by truck.

According to the IEA 2 degree scenario (2DS), CCS has to be scaled up from a few tens of Mtpa today to more than 6 gigatonnes per year in 2050.[135] In comparison, the current natural gas production amounted to approximately 2.5 gigatonnes in 2012.[136] Hence, in order to realize the 2DS, a massive investment in transportation infrastructure is needed. A significant part of the infrastructure will be offshore, both to reach attractive offshore storage sites and to avoid public acceptance issues related to transportation through populated areas.

The long industrial experience with natural gas transportation systems both onshore and offshore will certainly be of great help in achieving this goal, but in some aspects CO_2 behaves quite differently than natural gas, and this has to be taken into account when designing transport system. When optimizing the design of a transport system, it is important to take into account the whole chain. Currently, there are some uncertainties in predicting the properties of CO_2 mixed with typical impurities from CO_2 capture processes.

Hence, most transportation specification tends to be conservative, which could lead to a value chain that is off the optimum in terms of costs and efficiency.

4.2 Transport Methods

The main modes of CO_2 transport are by pipeline, ship or truck. Given the volumes required to meet the 2DS scenario, and the report focus offshore storage, this chapter will only discuss transport by pipeline and ship.

4.2.1 Pipeline transport

Pipelines are expected to be the backbone of a future CCS transport system in all regions. No other technology will be capable of handling the large transportation needed to mitigate global warming caused by anthropogenic emissions at an acceptable cost in terms of capital and efficiency.

[135] *Energy Technology Perspectives 2014*. (2014). Paris, France: International Energy Agency.

[136] *World Energy Outlook 2014*. (2014). Paris, France, www.worldenergyoutlook.org: International Energy Agency.

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Pipeline infrastructure for CO_2 transport will have many similarities with natural gas infrastructure, with conditioning and compression[137] at the source upstream and pipelines of similar materials and design and possibly hubs and booster stations before the terminus. Significant experience has been built over the decades with regards to offshore natural gas pipelines, summed up in standards such as the DNV standard for submarine pipeline systems.[138] Offshore pipelines are more expensive to install, operate, and maintain, but on the positive side they usually operate in a more predictable physical environment, especially in terms of temperature, and the public acceptance issues related to perceived safety seen especially with European CCS projects are not expected to apply for offshore CCS pipelines.

Under normal steady-state operating conditions, the natural gas offshore pipeline wisdom is expected to be readily applicable also for CO_2 for pipelines of similar dimensions and operating pressure with regards to offshore specific installation and impact from the environment. However, just like for onshore pipelines, the differences properties from natural gas have to be considered when designing CO_2 pipeline transportation systems. These specifics of CO_2 pipeline transport are fairly well covered in a number of high-level publications and recommendations.[139,140,141,142]

For instance, different gaskets materials and designs have to be used to cater for CO_2's high solubility in polymers, and CO_2's relatively low lubricity compared with hydrocarbons have to be taken into account when selecting rotating equipment and designing pigs for interior pipeline inspections. More importantly, CO_2 is most efficiently transported in dense phase, and in order to avoid two-phase flow, the pressure needs to be kept above the phase boundary during operation. Liquid water with CO_2 is corrosive, and like natural gas CO_2 forms hydrates with water. Hence, the impurity level of the CO_2 to be transported must be optimized. For these reasons, startup and

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[137] Aspelund, A. and Jordal, K. (2007). Gas conditioning—The interface between CO_2 capture and transport. *International Journal of Greenhouse Gas Control, 1*(3), 343-354.

[138] DNV, Det Norske Veritas AS. (2013). *Submarine Pipeline Systems* (Offshore Standard No. OS-F101). www.dnv.com.

[139] Doctor, R. and Palmer, A. (2005/2006). Transport of CO_2 *Carbon Dioxide Capture and Storage* (pp. 179-194). Geneva, Switzerland: IPPC (online) / Cambridge University Press.

[140] DNV, Det Norske Veritas AS. (2010). *DESIGN AND OPERATION OF CO2 PIPELINES* (RECOMMENDED PRACTICE No. DNV-RP-J202). www.dnv.com.

Pershad, H., et al. (2010). Development of a global CO_2 pipeline infrastructure Retrieved from http://decarboni.se/publications/development-global-co2-pipeline-infrastructure

[141] Forbes, S. M., et al. (2008). *CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage*. Washington, DC: World Resources Institute (WRI).

[142] *CO_2 Transportation - Is it Safe and Reliable?* (2010). Carbon Sequestration Leadership Forum.

Engebø, A. and Ahmed, N. (2012). *Activity 5: CO_2 transport*. Norway, http://www.gassnova.no/no/Documents/5.%20DNVFinalReportAct5CO2transport2012.pdf: Gassnova

Oosterkamp, A. and Ramsen, J. (2008). *State-of-the-Art Overview of CO_2 Pipeline Transport with relevance to offshore pipelines*. Haugesund, Norway: Polytec.

depressurization need more attention, particularly because rapid pressure drops are associated with strong cooling. Section 4.4 will provide a more detailed account of these topics.

To sum up, solutions for transporting CO_2 by pipeline exists. Compared with other modes of transport, such as shipping, the main advantage is potentially very large capacity and low operational costs, especially over relatively short distances and for high volumes, whereas the drawbacks are the investment costs and lack of flexibility.

4.2.2 Ship transport

Although transportation of CO_2 by ship has been common practice for more than 20 years, this mode of transportation has not been implemented in a CCS project yet. Up until now, there have only been small tonnage ships (approx.1000 tons) for supplying CO_2 to the food industry and other relatively small scale purchasers. Most of them were converted from liquefied petroleum gas (LPG) carriers. CO_2 transportation for CCS purposes will face different requirements, and there will be other challenges in terms of the design of the ships. The existing fleet transports CO_2 with a pressure of 15-20 bar and a temperature of about -30 °C. For larger volumes, current studies tend to use values for pressure and temperature in the neighbourhood of 8 bars and -50 °C (close to the triple point).[143]

Building pipelines over longer distances in combination with uncertain or smaller volumes of CO_2 can be quite expensive. In this case CO_2 transportation by ship can be a competitive solution, assuming the technology and systems are available. Ships can carry CO_2 far below their design capacity and has therefore a higher adaptability to fluctuation in CO_2 supply. This offers an option of collecting CO_2 from multiple sources and also injecting CO_2 at multiple storage sites. Their mobility and reusability increase flexibility in project planning, making it easier to expand or shrink the size of a project and to alter storage sites. But due to its nature of discrete services, the transportation mode generally needs additional facilities in comparison with pipeline systems: intermediate storage facilities and loading infrastructure at a port; and an unloading facility and intermediate storage facilities at or near a CO_2 storage site.

Currently, ship transport is foreseen as a potential kick-starter of offshore CO_2 transport and storage by fulfilling the need for reliable supply at the early stages of CCS or CO_2-EOR projects. Several studies into the technical feasibility of ship transport have been performed in recent years and a demonstration project is urgently needed to address some of the remaining uncertainties. Only a few technical issues remain, which are partly specific to each different storage location.

4.2.3 Hybrid solutions and value-chain perspectives

As discussed above, pipeline transport is most suitable for transportation of high volumes over many years and relatively short distances, whereas shipping is an attractive option for smaller

[143] *The Costs of CO_2 Transport*. (2011). http://www.zeroemissionsplatform.eu: European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP).

sources / sinks, longer distances, and its higher flexibility. In particularly in the early days of CCS, such flexibility could be very important. Compared with shipping, point to point links are particularly risky as the business case depends on the operation of a single source and single sink. For optimized operation, the transported volume should be close to capacity, but for sinks such as EOR fields, the demand will be far from constant. Hence, just like for natural gas, the CO_2 pipeline infrastructure should evolve into networks which will improve the flexibility and provide a more predictable transportation demand. Such networks could also include shipping hubs to connect marginal smaller industrial sources to the pipeline grid.[144] Similar to a natural gas network, a CO_2 network has to adhere to some CO_2 product standards. Here requirements from the storage operator might be given, whereas quality specifications for transport in some aspects will be a trade-off between transport cost and capabilities and conditioning costs at the capture site.

4.3 Current Status

4.3.1 CO_2 pipelines

4.3.1.1 Existing and planned infrastructure

A number of CO_2 pipeline projects are documented in the literature.[145,146,147] The largest CO_2 pipeline infrastructure in the world today exists in North America, chiefly in the US south-west/high plains region. This network has been constructed since the 1970s, partly financed by government incentives for enhanced oil recovery. The network was 6600 km long in 2010[145], including only high-pressure pipelines of length 16 km and longer with diameters varying between 4 and 30". The network is continuously under expansion.[148] Offshore there are significantly less pipelines deployed. Currently the only two operating projects are Sleipner[149,150] and Snøhvit[150,151]

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[144] Jordal, K., Morbee, J., and Tzimas, E. (2012). *ECCO strategies for CO_2 value chain deployment*. http://www.sintef.no/globalassets/project/ecco/results---deliverables/d2.3.7-ecco-strategies-for-co2-value-chain-deployment-sintef-er.pdf: ECCO Consortium.

[145] Bliss, K., et al. (2010). A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide. Retrieved from http://www.sseb.org/downloads/pipeline.pdf

[146] Noothout, P., et al. (2014). *CO_2 pipeline infrastructure*. http://ieaghg.org/docs/General_Docs/Reports/2013-18.pdf: Global CCS Institute, IEA Greenhouse Gas R&D Programme (IEAGHG).

CO_2 Pipelines (online database). from IEA Greenhouse Gas R&D Programme (IEAGHG): http://www.ieaghg.org/ccs-resources/co2-pipelines

[147] CO_2 Transportation - Is it Safe and Reliable? (2010). In Carbon Sequestration Leadership Forum, (CSLF) (Ed.), *inFocus - Carbon Capture and Storage*.

[148] Energy Pipelines CRC. (2014). Transport *The Global Status of CCS: 2014* (Ch. 8). Melbourne, Australia: Global CCS Institute. Retrieved from http://decarboni.se/publications/global-status-ccs-2014/8-transport

[149] Hansen, H., Eiken, O., and Aasum, T. O. (2005). *The path of a carbon dioxide molecule from a gas-condensate reservoir, through the amine plant and back down into the subsurface for storage. Case study: The Sleipner area, South Viking Graben, Norwegian North Sea*. Paper presented at the Offshore Europe 2005. Retrieved from http://dx.doi.org/10.2118/96742-MS

[150] Eiken, O., et al. (2011). Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit. *Energy Procedia, 4*, 5541-5548.

[151] Hansen, O., et al. (2013). Snøhvit: The History of Injecting and Storing 1 Mt CO_2 in the Fluvial Tubåen Fm. Ibid.*, 37*, 3565-3573.

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in Norway. Sleipner, in the North Sea, has been operating since 1996, but is a special case since the pipeline from the amine plant to the injection point is less than 1 km and made of stainless steel.

Figure 4-1: Left: Melkøya LNG plant, starting point of the world's only major existing offshore CO_2 pipeline[150,151]. Photo: Harald Pettersen / Statoil. Right: Installation of natural gas pipeline at the Sleipner field. Photo: Kim Laland/Statoil.

The Snøhvit project, located in the Barents Sea at 70° northern latitude, operates a 153 km long 8" pipeline from a coastal gas processing plant to the submarine injection point. Further European projects for offshore CCS pipeline transport are however in extended planning phase,[148,152] most notably:

- ROAD project,[153] Netherlands: Permitted / awaiting funding, 25 km 16" new offshore pipeline
- Peterhead project,[154] UK: FEED-phase, reuse of existing 100 km offshore natural gas pipeline
- Yorkshire and Humber project,[155] UK: FEED-phase, up to 24" new pipeline, 90 km offshore

4.3.1.2 Operation

The natural gas pipeline grid has been developed for decades. In Europe these pipelines have shown a remarkably low failure rate of 0.08 per 1000 km·years for pipelines of diameter 5 to 11"

[152] Hetland, J., et al. (2014). CO2 Transport Systems Development: Status of Three Large European CCS Demonstration Projects with EEPR Funding. Ibid., *63*(0), 2458-2466.

[153] http://road2020.nl/en/

[154] http://www.shell.co.uk/energy-and-innovation/the-energy-future/peterhead-ccs-project.html

[155] http://www.ccshumber.co.uk/the-pipeline.aspx

in the period 2004-2013, and even lower for larger diameter pipelines.[156] The primary cause of 35 percent of the incidents was external interference whereas corrosion caused 24 percent of the failures. Similar safety records are found in other developed regions, and have been used as a starting point also to analyze reliability of CO_2 onshore pipelines.[157,158]

For the US onshore pipelines, the Department of Transportation maintains a database of pipeline incidents.[159] Many groups have studied these data, and the results from some of these studies are summarized by Duncan and Wang.[158] The indication from these studies is that the failure rates are somewhat higher than for natural gas pipelines, up to a factor 2 or so. It has also been reported that different from natural gas pipelines, the largest cause of failures are corrosion.[160] It should be noted though, that in the United States the length of CO_2 pipelines is of the order of 1 percent of the natural gas pipelines, and with the small failure rates seen, the number of incidents is not statistically significant. So far no injury or fatality has been reported from CO_2 transportation, and most reported failures are minor leaks.

Due to the limited length and operational experience with offshore CO_2 pipelines, it should come as no surprise that no major incident has been reported publicly. Compared with onshore pipelines, it should be clear that offshore pipeline constitute an even smaller risk for public health. During operations of Snøhvit and Sleipner, experience with for instance shut-ins has been gained,[151] which could have impact also for the CO_2 transportation[161] due to transient effects.

4.3.1.3 CO2 transport specifications

It should be noted that the different CO_2 pipeline operators differs when it comes to CO_2 product specifications and pressure. For instance, the water content specifications vary between < 50 ppm to < 630 ppm [146]. From the information provided by Eiken et al.[149], the water content seems to be more than 1000 ppm at Sleipner, which could lead to hydrate formation or even water-rich liquid phase at prolonged shut-ins. From a corrosion perspective this example has less general relevance due to the use of stainless steel. Most of the US EOR pipelines are transporting gas from geological CO_2 sources.

Future CCS transport streams will have different impurities and composition depending on the capture and conditioning process. During the last decade, various CO_2 quality specifications for

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[156] *9th Report of the European Gas Pipeline Incident Data Group (period 1970 – 2013)*. (2015). Groningen, Netherlands, http://www.EGIG.eu: European Gas Pipeline Incident Data Group (EGIG).

[157] *Technical Guidance on Hazard Analysis for Onshore Carbon Capture Installations and Onshore Pipelines - A guidance document*. (2010). London, UK, http://www.energyinst.org: Energy Institute.

[158] Duncan, I. J. and Wang, H. (2014). Estimating the likelihood of pipeline failure in CO2 transmission pipelines: New insights on risks of carbon capture and storage. *International Journal of Greenhouse Gas Control, 21*, 49-60.

[159] http://www.phmsa.dot.gov/pipeline/library/data-stats

[160] *Mapping of potential HSE issues related to large-scale capture, transport and storage of CO_2*. (2008). Stavanger, Norway, http://www.ptil.no/getfile.php/PDF/Ptil%20CCS%202008.pdf: Det norske veritas (DNV).

[161] de Koeijer, G., Hammer, M., Drescher, M., and Held, R. (2014). Need for experiments on shut-ins and depressurizations in CO_2 injection wells. *Energy Procedia, 63*, 3022-3029.

pipeline transport have been proposed.[162] These standards vary a great deal in terms of for instance content of water (50 to 500 ppm) and other impurities and CO_2 overall purity (95 to 99.5 percent).

4.3.2 CO_2 Ship Transport

Although there is no existing example of CO_2 transport by ship in relation to a CCS project, there have been at least six small CO_2 tankers for businesses such as carbonated beverage, food chilling/ freezing and greenhouses in northern Europe. There is one ship designed as a CO_2 carrier. The ship, operated by a Dutch shipping company Anthony Veder since 1999, carries up to 1,250 m^3 of CO_2 at 18 barg and -40 °C.[163] The rest of the ships were all converted from LPG tankers. These ships, including two retired, are/ were owned by a Norwegian company Yara International and operated by Larvik Shipping, and capable of carrying CO_2 of up to 900 to 1,800 tonnes at 15–20 bara and around -30 °C.[164,165,166]

There have been multiple proposals, studies and designs for shipping solutions executed mainly in Europe in and East Asia. These include a shipping solution developed by TEBODIN, Anthony Veder and VOPAK[167] for the development of a liquid logistics shipping concept between Rotterdam and various storage locations in the Netherlands and Denmark. Other examples include studies published by SINTEF,[168] IFPEN, Chiyoda Corp.,[169] and DSME,[170] Knudsen et al. and

[162] de Visser, E., et al. (2008). Dynamis CO2 quality recommendations. *International Journal of Greenhouse Gas Control, 2*(4), 478-484.

Buit, L., et al. (2011). *Standards for CO_2*. Netherlands, http://www.co2europipe.eu/: Towards a transport infrastructure for large-scale CCS in Europe (CO2Europipe).

Matuszewski, M. and Woods, M. (2012). *CO_2 Impurity Design Parameters*. United States, http://www.netl.doe.gov//research/energy-analysis/publications/: National Energy Technology Laboratory (NETL).

Høydalsvik, H. (2013). *Gassnova CO_2 Capture, Transport and Storage - Mongstad CO_2 product specification*. Norway: Gassnova.

[163] http://www.anthonyveder.com/fleet/coral-carbonic/

[164] http://www.yara.com/media/news_archive/Yara_co2_ships.aspx

[165] http://www.larvik-shipping.no/

[166] Peter Brownsort (2015). Ship transport of CO_2 for Enhanced Oil Recovery – Literature Survey, SCCS

[167] Vermeulen, T. (2011). *Knowledge sharing report – CO_2 liquid logistics shipping concept (LLSC): overall supply chain optimization.* The Hague, The Netherlands, http://www.globalccsinstitute.com/publications/co2-liquid-logistics-shipping-concept-llsc-overall-supply-chain-optimization: Global CCS Institute.

[168] Aspelund et al., 2006. Ship Transport of CO_2: Technical Solutions and Analysis of Costs, Energy Utilization, Exergy Efficiency and CO_2 Emissions, *Chem. Eng. Research and Design,* 84, 847-855.

[169] Omata, A. (2011). *Preliminary feasibility study on CO_2 carrier for ship-based CCS.* http://www.globalccsinstitute.com/publications/preliminary-feasibility-study-co2-carrier-ship-based-ccs: Global CCS Institute.

Omata, A. (2012). *Preliminary feasibility study on CO_2 carrier for ship-based CCS. Phase 2: unmanned offshore facility*. http://www.globalccsinstitute.com/publications/preliminary-feasibility-study-co2-carrier-ship-based-ccs-phase-2-unmanned-offshore: Global CCS Institute.

[170] Yoo, B.-Y., Lee, S.-G., Rhee, K.-P., Na, H.-S. and Park, J.-M. (2011). New CCS system integration with CO_2 carrier and liquefaction process. 10th International Conference on Greenhouse Gas Control Technologies, 2011, Amsterdam. Energy Procedia, 4: 2308-2314. Elsevier Science

others. Furthermore, there is ongoing or recently-completed research on CO_2 shipping within several national research programs like CATO (Netherlands), CLIMIT (Norway) , MOE (Japan) and European research programs such as CO2Europipe[171] and Cocate[172] (completed). These examples provide a solid scientific basis to further development of CO_2 transport by ship.

Furthermore, operational experience exists on individual elements of the liquid logistics chain. For example, commercial activities like Yara's Sluiskil (The Netherlands) fertilizer industry demonstrate CO_2 onloading and offloading systems.

4.3.3 Costs

Some cost figures for CCS pipeline projects are collected in the IEAGHG CO_2 pipeline database[146]. Generally, cost estimates for the CO_2 transport vary greatly, from a few dollars to several tens of dollars per CO_2 tonne transported, greatly dependent on factors such as terrain, transport length, capacity, and utilization rates.[139,173,174,175] The transportation can hence be a significant part of both the cost and energy use of a CCS system, especially when offshore transport is needed. Hence, it is important to optimize the efficiency and investment and operational costs of the transport system while ensuring safety in order to lower the threshold of large-scale CCS deployment.

All the studies cited above were mainly using corresponding costs for hydrocarbon transport as a starting point. The NETL study[173] is generally concerned with onshore transport in the United States, but provided a handy formula to calculate the costs in terms of whereas other studies also consider offshore pipelines and shipping in more detail. A thorough study should also calculate the cost per avoided amount of CO_2, rather than transported. Generally speaking, pipeline has a rather high capex cost which scale approximately proportionally with distance, and small operational cost. Shipping, on the other hand, has much lower investment costs, but higher operational cost with a minimum per trip due to loading/liquefaction and unloading/heating/compression. Hence, shipping is favored by long distances and smaller volumes, whereas pipelines are favored by short distances and large volumes. For short distances the choice will always be pipelines, whereas for large volumes the jury seems to be out in terms

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[171] www.co2europipe.eu.

[172] http://projet.ifpen.fr/Projet/jcms/c_7861/fr/cocate.

[173] Grant, T., Morgan, D., and Gerdes, K. (2013). *Carbon Dioxide Transport and Storage Costs in NETL Studies*. USA, http://www.netl.doe.gov/research/energy-analysis/quality-guidelines-qgess: United States Department of Energy, National Energy Technology Laboratory (NETL).

[174] *The Cost of CO_2 Transport*. (2011). http://www.zeroemissionsplatform.eu: European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP).

Roussanaly, S., Bureau-Cauchois, G., and Husebye, J. (2013). Costs benchmark of CO_2 transport technologies for a group of various size industries. *International Journal of Greenhouse Gas Control, 12*, 341-350.

[175] Roussanaly, S., Brunsvold, A. L., and Hognes, E. S. (2014). Benchmarking of CO_2 transport technologies: Part II – Offshore pipeline and shipping to an offshore site. Ibid.*, 28*, 283-299.

Geske, J., Berghout, N., and van den Broek, M. (2015). Cost-effective balance between CO_2 vessel and pipeline transport. Part I – Impact of optimally sized vessels and fleets. Ibid.*, 36*, 175-188.

of break-even distance between shipping and pipelines[175]. It can be noted that since pipelines require a large up-front investment, the alternative constitute a large financial risk than shipping, and that the cost calculations both are affected by the ship capacity and pipeline lifetime and ramp-up time.

4.4 Technical Challenges or Technology Gaps

4.4.1 Pipeline transport - challenges/gaps

It should be noted, that most of the technical challenges discussed below are just as relevant for onshore pipeline. In many aspects, offshore pipelines could be at an advantage, due to their more stable temperature, perhaps higher heat transfer to the surroundings, and higher external hydrostatic pressure. Aspects related to dynamic phenomena and impurities are however also highly in other parts of the CO_2 value chain, such as injection[161]. Most of the challenges can be avoided by conservative design and sufficient safety margins for instance in terms of pipeline design, level of impurities and compression level. For a more optimized and cost efficient transportation system, additional targeted research is however recommended.

4.4.1.1 CO_2 properties and impact of impurities

The thermodynamic properties of pure CO_2 are well described by the Span-Wagner equation of state[176] and illustrated in the phase diagram of Figure 4-2 and can be compared with natural gas in Figure 4-3. Different from natural gas, the critical point of CO_2 is above the typical environmental range relevant for offshore pipelines between approximately 0 and 25 °C, meaning there is a phase boundary between liquid and gas. For better efficiency and smaller volumes, the preference will usually be to transport gas in the liquid state, although gas phase transport has also been proposed for storage sites with low pressure. Hence, unlike natural gas pipeline systems, pumps are often used to boost the pressure of the CO_2 fluids[137,141]. Two-phase flow is usually undesirable, as it could lead to slug flow and destroy compressors or pumps that are not designed for it. In order to avoid two-phase flow, the operation point should be away from the phase boundary, meaning that there is a theoretical lower limit for the operational pressure in the pipeline, unlike commercial natural gas pipelines which operate at a large range of pressures.

In some cases, for instance when the CO_2 storage field has low pressure, it is not possible to be above the dew point pressure all the way to the injection point. In the ROAD project where the plan is to use a depleted gas field as a storage site, it is proposed to avoid this problem by heating the CO_2 far above the critical temperature at the pipeline inlet such that the pressure is below phase boundary as the temperature passes the critical point as the gas is being cooled.[177] This will lower

[176] Span, R. and Wagner, W. (1996). A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. *Journal of Physical and Chemical Reference Data, 25*(6), 1509-1596.

[177] Uilenreef, J. and Kombrink, M. (2013). *Flow Assurance and Control Philosophy ROAD - Special Report for the Global Carbon Capture and Storage Institut*. http://decarboni.se/sites/default/files/publications/114746/road-

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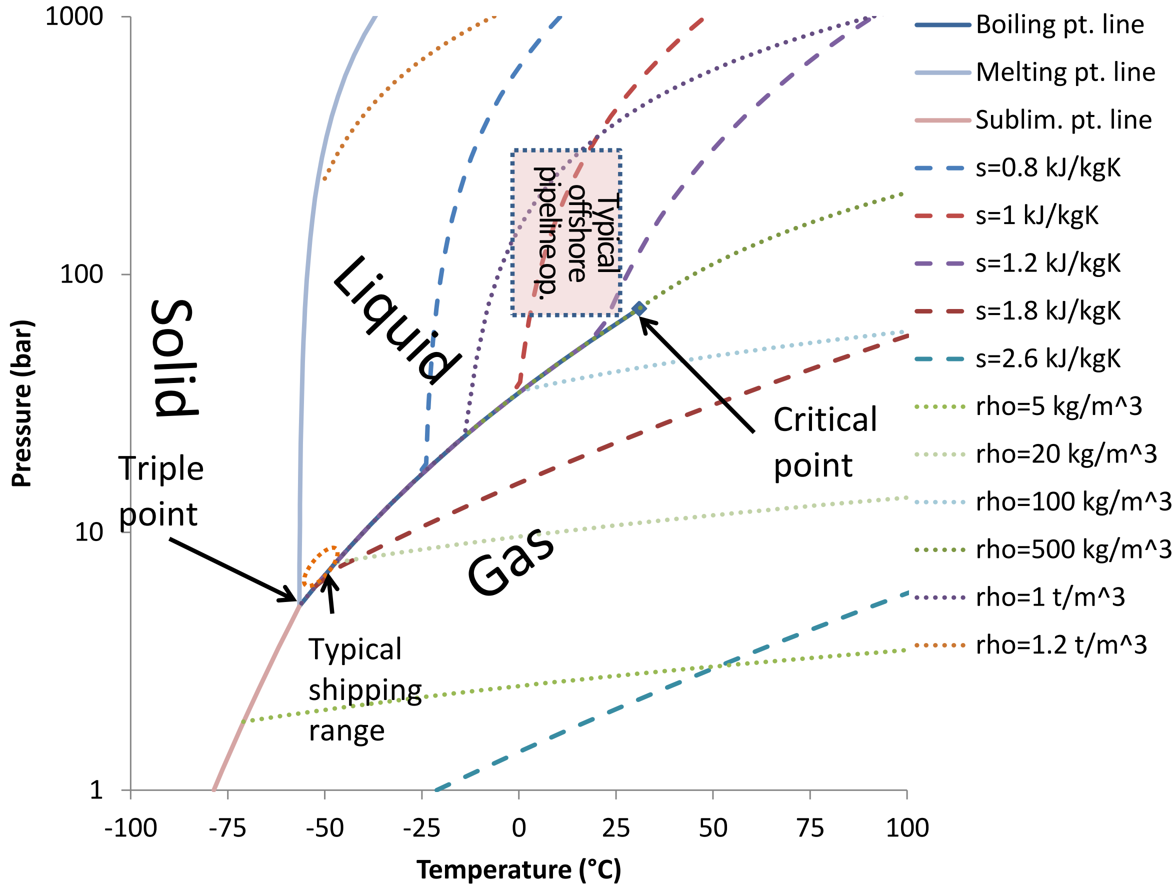

Figure 4-2: Phase diagram of pure CO_2, including curves for constant density (ρ) and entropy (s), calculated from the Span-Wagner equation of state.

CO_2 density inside and hence capacity of the pipeline, but the injection will take place in the liquid phase as the reservoir pressure has increased.

project-flow-assurance-and-control-philosophy.pdf: ROAD | Maasvlakte CCS Project C.V. / Global Carbon Capture and Storage Institute.

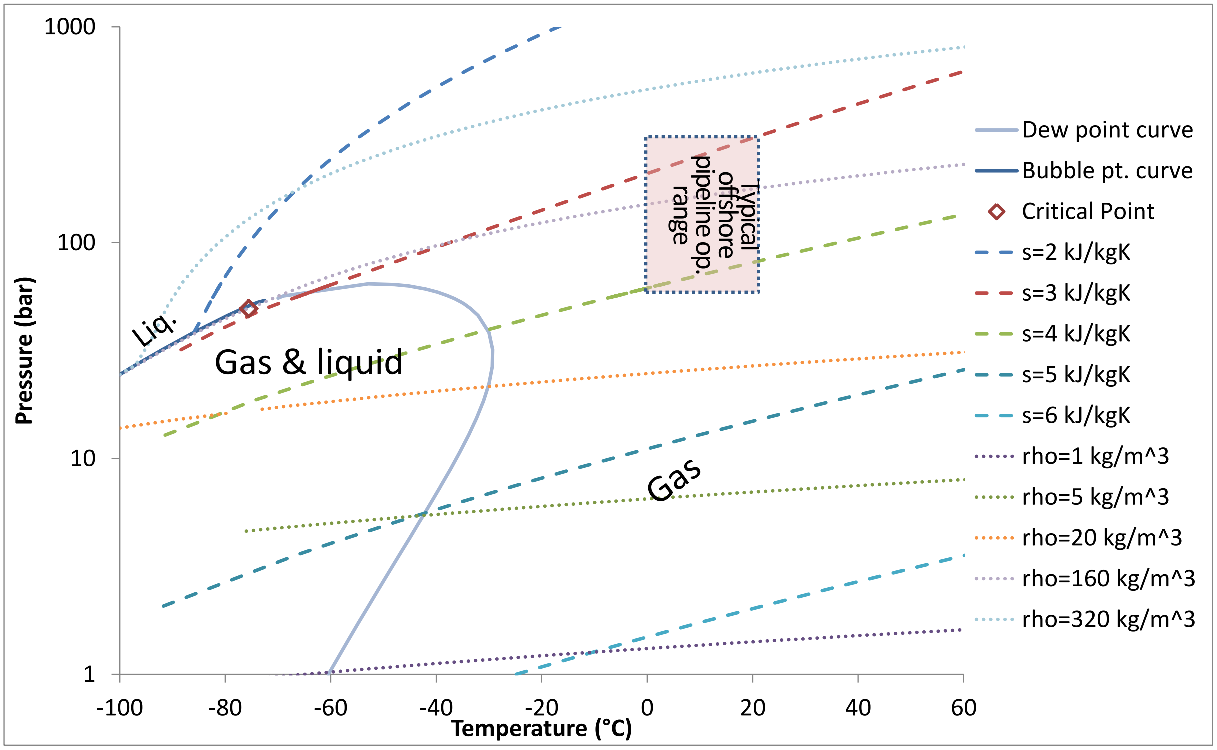

Figure 4-3: Typical phase diagram of natural gas within pipeline spec., including curves for constant (ρ) and entropy (s).

With impurities present, the phase boundary will split and form a two-phase envelope and complicate the diagram. Typically the upper pressure for which two phases form, the cricondenbar, may increase with the presence of non-condensable impurities such as nitrogen.[178] Other challenges exist with other impurities. For instance, water may form hydrates with CO_2 at lower water concentrations than needed for a water rich-phase,[179] a behavior which can be enhance by other impurities such as methane.[180] Impurities are also seen to have large impact on important properties such as density.[178]

There is currently a lack of accurate experimental data for CO_2 mixed with impurities regarding important properties such as phase behavior, density (needed for dimensioning and metering), viscosity (needed for pressure loss calculations), and thermal conductivity (needed e.g., to

[178] Løvseth, S. W., et al. (2013). CO_2Mix Project: Experimental Determination of Thermo Physical Properties of CO_2-Rich Mixtures. *Energy Procedia, 37*, 2888-2896.

[179] de Koeijer, G., et al. (2011). CO_2 transport–Depressurization, heat transfer and impurities. Ibid.*, 4*, 3008-3015.

[180] Song, K. Y. and Kobayashi, R. (1990). The water content of a carbon dioxide-rich gas mixture containing 5.31 Mol% methane along the three-phase and supercritical conditions. *Journal of Chemical and Engineering Data, 35*(3), 320-322.

calculate dynamic phenomena).[181] Hence, awaiting these experimental data and corresponding reference models,[182] current standards on impurities tend to be very conservative.

4.4.1.2 Corrosion

A problem of less importance in natural gas pipelines is the well-known fact that CO_2 dissolved in water forms carbonic acid which could cause serious corrosion. Hence, since stainless steel is ruled out due to costs for a large scale transportation system, a water-rich liquid phase should be avoided in CO_2 pipelines at all times. Unfortunately, the water solubility is much lower in the gas phase than in the liquid phase.[183] To complicate matters more, the presence of other impurities, like methane, SO_2, and NO_x is known to lower the solubility further,[184] and chemical reactions between impurities may have a negative effect.[185]

4.4.1.3 Dynamic phenomena

During an operation of a CCS pipeline, transient changes in pressure and flow must be expected, usually planned during startup, well shut-ins etc., but an operator should also be prepared for unintentional rapid depressurizations. Just like natural gas, rapid pressure changes are associated with changes in temperature. During depressurization of a CO_2-pipeline, the state point of the fluid fairly quickly falls down to the boiling point line,[179] in the ideal case following one of the isentropic lines shown in Figure 4-2, at which point the liquid will start to boil and temperature continues to fall towards the triple point. At the same time, the shock wave velocity will slow down, dependent

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[181] Li, H., Jakobsen, J. P., Wilhelmsen, Ø., and Yan, J. (2011). PVTxy properties of CO_2 mixtures relevant for CO_2 capture, transport and storage: Review of available experimental data and theoretical models. *Applied Energy, 88*(11), 3567-3579.

Li, H., et al. (2011). Viscosities, thermal conductivities and diffusion coefficients of CO_2 mixtures: Review of experimental data and theoretical models. *International Journal of Greenhouse Gas Control, 5*(5), 1119-1139.

Gernert, G. J. (2013). *A NEW HELMHOLTZ ENERGY MODEL FOR HUMID GASES AND CCS MIXTURES.* Fakultät für Maschinenbau, Ruhr-Universität Bochum, Bochum, Germany.

[182] Gernert, J., Jäger, A., and Span, R. (2014). Calculation of phase equilibria for multi-component mixtures using highly accurate Helmholtz energy equations of state. *Fluid Phase Equilibria, 375*, 209-218.

[183] Spycher, N., Pruess, K., and Ennis-King, J. (2003). CO_2-H_2O mixtures in the geological sequestration of CO_2. I. Assessment and calculation of mutual solubilities from 12 to 100°C and up to 600 bar. *Geochimica et Cosmochimica Acta, 67*(16), 3015-3031.

[184] Austegard, A., Solbraa, E., Koeijer, G. D., and Mølnvik, M. J. (2006). THERMODYNAMIC MODELS FOR CALCULATING MUTUAL SOLUBILITIES IN H_2O–CO_2–CH_4 MIXTURES. *Chemical Engineering Research and Design, 84*(A9), 781–794.

Ahmad, M. and Gersen, S. (2014). Water Solubility in CO_2 Mixtures: Experimental and Modelling Investigation. *Energy Procedia, 63*, 2402-2411.

Xiang, Y., et al. (2012). The upper limit of moisture content for supercritical CO_2 pipeline transport. *The Journal of Supercritical Fluids, 67*, 14-21.

[185] Halseid, M., Dugstad, A., and Morland, B. (2014). Corrosion and Bulk Phase Reactions in CO_2 Transport Pipelines with Impurities: Review Of Recent Published Studies. *Energy Procedia, 63*, 2557-2569.

on the degree of phase equilibrium[186] and impurity level.[187] Hence, such sudden drop in pressure is associated with formation of liquid phase, and in the worst case in the presence of water, hydrate plugs. These are complex phenomena involving coupling between fluid dynamics and thermodynamics.[187]

One example where understanding of transient phenomena in CO_2 pipelines are needed, is the study of running fractures. Such fractures can propagate due to the inner pressure of the pipeline, and is hence dependent on the relation between the propagation velocity of the fracture and the pressure wave front. Due to the drop in the shock wave velocity associated with the phase boundary, running fractures may be a more likely scenario in CO_2 pipelines than in natural gas pipelines. Occurrence of running fractures could constitute a major setback for CCS, and be can be prevented by ensuring sufficient pipeline wall thickness or material quality or introduce crack arrestors. Large decreases in temperatures due the Joule-Thomsen effect and boiling has to be taken into consideration when evaluating the material parameters, and steels with low ductile-brittle transition temperature.[188] The current industry standard is to use the empirical uncoupled models such as Battelle method and HLP approach.[189] Unfortunately, these methods are not necessarily conservative, and a more rigorous approach should probably be applied.[190]

4.4.2 Ship transport

Several studies into the technical feasibility of ship transport have been performed in recent years. Only a few technical issues remain, which are partly related to the storage location itself. The remaining technical challenges are related to offshore unloading (interface between ship and well head), injection conditions, CO_2 processing on the platform in case of an EOR project and onshore unloading at a pipeline terminal. In order to remove these barriers a real demonstration project is needed.

4.4.2.1 Offshore unloading

The offshore offloading system can be viewed as the interface between the ship and the field. This implies that a conversion needs to be made from the CO_2 conditions within the ship (typically, liquid CO_2 at a pressure of around 8 bar and temperature of around -50 °C) and the conditions acceptable to the reservoir (pressure, temperature, flow rate). In order to match these requirements,

[186] Flåtten, T. and Lund, H. (2011). Relaxation two-phase flow models and the subcharacteristic condition. *Mathematical Models and Methods in Applied Sciences, 21*(12), 2379-2407.

[187] Munkejord, S. T., Jakobsen, J. P., Austegard, A., and Mølnvik, M. J. (2010). Thermo- and fluid-dynamical modelling of two-phase multi-component carbon dioxide mixtures. *International Journal of Greenhouse Gas Control, 4*(4), 589-596.

[188] Nordhagen, H. O., et al. (2012). A new coupled fluid–structure modeling methodology for running ductile fracture. *Computers and Structures, 94–95*, 13-21.

[189] Maxey, W. (1974). *Fracture initiation, propagation, and arrest*. Paper presented at the Fifth Symposium on Line Pipe Research.

Sugie, E., et al. (1982). A study of shear crack propagation in gas-pressurized pipelines. *Journal of Pressure Vessel Technology, 104*(4), 338-343.

[190] Aursand, E., et al. (2014). CO_2 Pipeline Integrity: Comparison of a Coupled Fluid-structure Model and Uncoupled Two-curve Methods. *Energy Procedia, 51*, 382-391.

the flow properties in hoses, pipelines and well(s) will have to be analyzed. This will in turn allow determining pressurization and heating capabilities needed on board the vessel. The design of the offshore offloading facility is likely to be dependent on the reservoir properties (depth, pressure), as well as the maximum period level of intermittency allowed for the injection. In addition to pressurization and heating requirements on the ship, an important aspect of this optimization work will also be to maximize the offloading rate in order to minimize the offloading time of the vessel.

Depending on these parameters, temporary storage near the platform may be required. A solution for offshore offloading may need to be developed for each different storage location. Several engineering studies have been executed to further detail offshore offloading systems, which may include additional systems (compressors, heaters) on the ship itself, or a temporary storage barge.[191] The challenge is to design a system that provides enough flexibility to be connected to different storage locations with different requirements.

4.4.2.2 Injection conditions and temperatures

The injection of cold CO_2 from the ship into a reservoir could cause ice formation in the riser including a possible phase transition in the CO_2. Various combinations of pressure, temperature and flow rate should be analyzed to see how typical reservoirs respond during injection and also during the periods between the injections. It is expected that the temperature of the CO_2 at the well head should be above zero, to avoid freezing of the near-well area at depth (followed by thawing during interruptions in the injection). Further research needs to be done in order to improve the understanding of the allowed ranges of well-head temperatures.

4.4.2.3 CO_2 separation offshore

Studies of transport of CO_2 by ship often consider a connection to EOR projects. Onshore EOR, as in the United States, is typically done as WAG flooding. That means that the injection of gas alternates with that of water. If applied offshore such practice may benefit from CO_2 transportation by ship. This is because WAG flooding will not need a continuous flow of CO_2, but rather a batch flow, at least as seen from the individual well.

Once the injected CO_2 breaks through to the producing well, any gas injected afterwards will follow that path, reducing the overall efficiency of the injected fluids to sweep the oil from the reservoir rock. This means that the full (maximum) supply of CO_2 to an EOR field will only be needed for a limited period of time, before the volumes of supplementary CO_2 will be reduced. It is expected that, typically, the demand for CO_2 in an EOR project is at a maximum at the start, steadily decreasing until the end of the project.

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[191] E.g., see Vermeulen, T. (2011). *Knowledge sharing report – CO_2 liquid logistics shipping concept (LLSC): overall supply chain optimization.* The Hague, The Netherlands, http://www.globalccsinstitute.com/publications/co2-liquid-logistics-shipping-concept-llsc-overall-supply-chain-optimization: Global CCS Institute.

4.4.2.4 Onshore unloading at a pipeline terminal

The design, safety, and practicality of CO_2 import by ship into onshore (near-shore) pipeline terminals need to be further developed, especially on the design and costs of equipment and installations (re-gasifiers, re-heaters, pumps, temporary storage).

4.5 R&D Opportunities

With the technical challenges and knowledge gaps discussed above, there are certainly areas that call for more research, and several groups around the world have started the job.[192] As already indicated above and in CLSF 2013 Technology Roadmap,[193] there is a need for accurate measurements of phase behavior and other properties of CO_2 mixed with impurities at relevant conditions and develop correspondingly accurate models. There is also a need to advance the current flow models, which include non-equilibria thermodynamics. Such models needs to be tuned with accurate transient flow measurements.[161,194] In addition to these fundamental aspects to optimize the operation of CO_2 pipelines, it is probably also room for improving associated equipment and processes, for instance relating to compression, gaskets, pipe inspections, metering etc.

For ship transport, only a few technical issues remain, which are partly related to the storage location itself. The remaining technical challenges are related to offshore loading, injection conditions, CO_2 processing on the platform in case of an EOR project and onshore unloading at a pipeline terminal. In order to remove these barriers a real demonstration project is needed.

Most likely, the main barrier for CO_2 offshore transportation is not of technical nature, but a matter economics and organization. Hence, there will still be need to work on benchmarking and cost estimates. Future CCS chains will be complex, with a variety of sources and storage sites which will have different types of requirements. In such a chain, it is important to realize that cost saved in one process, e.g., conditioning, could lead to additional costs at another place, e.g., transport.

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[192] Some research programs and larger projects on CCS transport around the world include
BIGCCS: http://www.bigccs.no
CO_2PipeTrans2: https://www.dnvgl.com/oilgas/innovation-development/joint-industry-projects/co2pipetrans.html
UKCCRS: https://ukccsrc.ac.uk/
Energy Pipelines CRC: http://epcrc.com.au/
Pipeline Research Council International: http://prci.org/index.php/about/
IMPACTS: http://www.sintef.no/projectweb/impacts/
CO_2Quest: http://www.co2quest.eu/

[193] *Carbon Sequestration Leadership Forum Technology Roadmap 2013*. (2013). Washington DC, USA, http://www.cslforum.org/publications/documents/CSLF_Technology_Roadmap_2013.pdf: Carbon Sequestration Leadership Forum (CSLF).

[194] Drescher, M., et al. (2014). Experiments and modelling of two-phase transient flow during pipeline depressurization of CO_2 with various N_2 compositions. *Energy Procedia, 63*, 2448-2457.
Botros, K. K., et al. (2010). Transferability of decompression wave speed measured by a small-diameter shock tube to full size pipelines and implications for determining required fracture propagation resistance. *International Journal of Pressure Vessels and Piping, 87*(12), 681-695.

Hence, optimization must be performed on a chain level. Further, methodology for large scale infrastructure design criteria and planning will have to be developed further, building on existing tools.[195] Such a work should include evaluation of global/regional/national government incentives and legal issues.

4.6 Regulatory Requirements

4.6.1 Existing national and regional codes

Most markets currently accommodate CO_2 pipeline transport by adjusting existing regulations relating to other pipeline transport, for example:

- United States: 49 Code of Federal Regulations (CFR) part 195.[196] CO_2 added to "Transportation of hazardous liquids by pipeline" in 1989, associated standard ASME B31.4.[197]
- Canada: Parts of CSA Z662.
- Europe: CCS directive 2009/31/EC established a framework for regulatory regime for pipeline transport,[198] member state to implement specific codes regarding safety standards.

A recommended practice document has been developed by DNV for CO_2 pipeline transport[138], and DNV has also written a standard for submarine pipeline systems.[199] Currently, an ISO standard is being developed for CO_2 transportation,[199] apparently supplementing the existing ISO standards for gas pipelines and building on the recommended practices by DNV.[148]

For shipping, regulations should be international, and existing frameworks such as UN Recommendations on the Transport of Dangerous Goods - Model Regulations should be a good starting point.[200] The design and construction of CO_2 tankers should comply with the IGC Code adopted by International Maritime Organization (IMO). The Code is to provide an international

[195] E.g.: Jakobsen, J. P., Tangen, G., Nordbø, Ø., and Mølnvik, M. J. (2008). Methodology for CO2 chain analysis. *International Journal of Greenhouse Gas Control, 2*(4), 439-447.
Løvseth, S. W. and Wahl, P. E. (2012). ECCO Tool: Analysis of CCS value chains. *Energy Procedia, 23*, 323-332.
Jakobsen, J. P., Roussanaly, S., Mølnvik, M. J., and Tangen, G. (2013). A standardized Approach to Multi-criteria Assessment of CCS Chains. Ibid*., 37*, 2765-2774.
Eickhoff, C., et al. (2014). IMPACTS: Economic Trade-offs for CO_2 Impurity Specification. Ibid*., 63*, 7379-7388.
Business models for commercial CO_2 transport and storage - Delivering large-scale CCS in Europe by 2030. (2014). Retrieved from http://www.zeroemissionsplatform.eu/library/publication/252-zepbusmodtransportstorage.html

[196] https://www.law.cornell.edu/cfr/text/49/part-195

[197] https://law.resource.org/pub/us/cfr/ibr/002/asme.b31.4.2002.pdf

[198] http://eur-lex.europa.eu/ , see also:
Haan-Kamminga, A. and Roggenkamp, M. (2010). CO_2 Transportation in the EU: Can the Regulation of CO_2 Pipelines Benefit from the Experiences in the Energy Sector? Retrieved from http://dx.doi.org/10.2139/ssrn.1701126

[199] International Organization for Standardization, (ISO). (2015). *Carbon dioxide capture, transportation and geological storage* (Approved for registration as draft international standard No. ISO/CD 27913).

[200] http://www.unece.org/?id=3598

standard for the safe transport by sea in bulk of liquefied gases and certain other substances, by prescribing the design and construction standards of ships involved in such transport and the equipment they should carry so as to minimize the risk to the ship, its crew and to the environment, having regard to the nature of the products involved.[201]

However there is one legal issue on the transboundary transportation of CO_2 that need still need to be resolved. The London protocol (global agreement on regulating dumping of wastes at sea) prohibits countries to export their CO_2 to another country for storage in the marine environment (see chapter 8.2 for a detailed explanation). Therefore the export amendment was adopted in 2009 in order to allow export of CO_2 for geological storage. Two thirds of member states need to ratify before it comes into force. This currently means 30 countries need to ratify it. To date just two have: Norway and UK. The exception is if the CO_2 is a purpose other than dumping, such as for enhanced oil recovery. The slow ratification process can have a negative impact on the development of transboundary CCS projects the coming years.

CO_2 export by pipeline or ships for CO_2 dumping at sea is currently prohibited under the London Protocol. To allow this, its Article 6 had amended in 2009 but the amendment has not come into force yet. The detail is discussed in 8.2.1.1 in this report.

To conclude, regulations exist for CO_2 transport, but these should be optimized as the technology and market mature.

4.7 Recommendations

Just like CO_2 capture and offshore storage, technology and solutions for CO_2 transport exists and have shown to be robust during decades of operation. Offshore CO_2 transportation is more limited, but can benefit from substantial operational experience from natural gas pipelines. Compared with onshore pipeline transportation, offshore CO_2 transport will probably be more expensive, but also there are also some distinct advantages:

- Less exposed to political controversy related to perceived public risk and routing
- Shipping is a mode of transport with large flexibility in a start-up phase and to tie in smaller CO_2 sources and/ or smaller CO_2 sinks
- More stable physical environment.

To realize the international ambitions to mitigate global warming, the CO_2 transportation probably has to increase by a factor of approximately 100, and transportation of CO_2 will be an important contributor to the overall costs for CCS. Hence, optimization of current practices is important, on areas such as CO_2 product specifications and sharing of infrastructure to optimize utilization. Specific areas of research to achieve these goals have been described.

[201] http://www.imo.org/OurWork/Environment/PollutionPrevention/ChemicalPollution/Pages/IGCCode.aspx

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5 Risk analysis for offshore CO_2 storage

The risk management process for the geological storage of CO_2 would be implemented systematically for each storage project (Figure 5-1).[202] In the process, risk assessment can be performed using the three stage approach consisting of identification, analysis and evaluation. Risk analysis is the process to comprehend the nature of risk and determine the level of risk.

Proposals for an offshore CO_2 storage license ought to be subjected to the completion of appropriate risk analysis as part of a required environmental impact statement, including potential amelioration of risk by safety monitoring equipment.

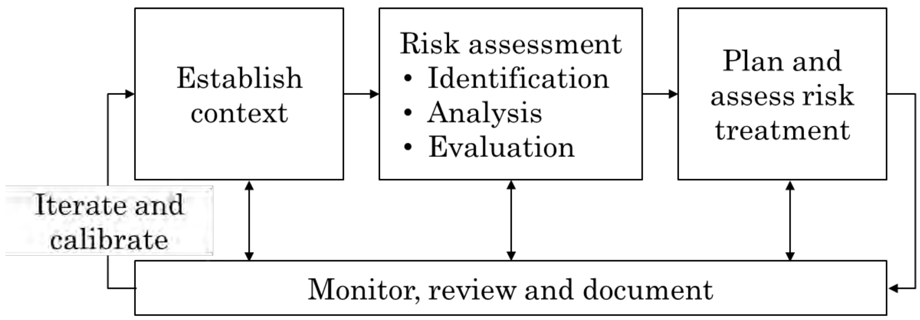

Figure 5-1. Recommended risk management process for CO_2 geological storage.[1] Risk assessment consists of risk identification (the process of finding, recognizing and describing risks), risk analysis (the process to comprehend the nature of risk and to determine the level of risk), and risk evaluation (the process of comparing the results of risk analysis with the risk criteria to determine whether the risk and/or its magnitude is acceptable and tolerable).

5.1 Potential Risks

General potential risks and their consequences associated with CO_2 storage operations are shown in Table 5-1. Among the potential consequences, issues concerning the marine environment and resources would be specific to offshore storage. Issues regarding induced seismicity are the same for both onshore and offshore storage, but monitoring tools and techniques would be different. Thus monitoring technology for passive and induced seismicity is described in Chapter 7.

Public concern regarding the environmental risks associated with CCS, in particular the possibility of CO_2 leakage from a reservoir into the marine environment, has the potential for stalling the wide-scale industrial deployment of CCS.[203] While it can be argued that the likelihood of CO_2

[202] DNV, 2012. RECOMMENDED PRACTICE, DNV-RP-J203, Geological Storage of Carbon Dioxide. Available online: https://exchange.dnv.com/publishing/Codes/download.asp?url=2012-04/rp-j203.pdf. Last accessed 23/2/2015

[203] Van Noorden, R., 2010. Carbon sequestration: buried trouble. Nature 463, 871–873.

leakage from a reservoir is extremely small,[204] secure scientific and public acceptance of offshore CO_2 storage is needed for the wider deployment of this technology.

Table 5-1 Potential risks associated with CO_2 storage operation

Risk Category	Potential risk	Potential Consequence
Injection	Deformation of rock stratum	Degradation of storage performance by unexpected CO_2 migration
		Damages resulting from induced seismicity
Leakage	Human health	Acute or chronic CO_2 impacts on employees or the general public
	Environmental	Impacts on groundwater or seawater
		Impacts on surface or near-surface ecosystem
	Property	Damages to natural resource rights (mineral, water, agriculture, forestry and fisheries)
		Diminution of properties value in the vicinity of storage sites
		Business interruption for CCS operator or for neighboring properties if remediation is required
	Financial	Entailing potential for return on investment, contractual liabilities in the carbon market
		Entailing credit risk related to obligations for long-term operations and maintenance at CCS sites

5.2 Monitoring Tools for Risk Control

Potential continuous leakage of CO_2 into the water column may occur from a pipeline, an injection well, an abandoned well and through the seabed sediments following escape via a geologic pathway such as permeable fault.

[204] IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

When gaseous CO_2 ($CO_2(g)$) dissolves in seawater reacting with water through a series of four chemical equilibria (below) that increase the concentrations of the carbon species: dissolved carbon dioxide ($CO_2(aq)$), carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-):

$$CO_2(g) \leftrightarrow CO_2(aq)$$

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

These reactions lead to a net increase in hydrogen ions (H^+). This results in a reduction in pH, or an increase in acidity of the seawater (acidification).

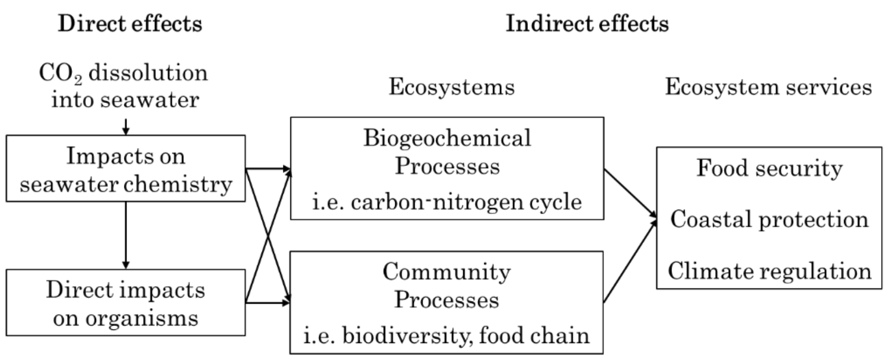

Figure 5-2. Impacts of potential CO_2 leakage on marine organisms, ecosystems and ecosystem services. Direct impacts on organisms are summarized in Table 5-2

A decline in seawater pH is associated with a fall in both carbonate ion (CO_3^{2-}) and the saturation states (Ω) of various calcium carbonates ($CaCO_3$). Hence, the seawater solubilities of three forms of calcium carbonates, namely calcite, magnesium-calcite, and aragonite, increase, making it harder for some marine biota to maintain heathy shells and other structures.

These chemical alterations of seawater resulting from CO_2 dissolution impacts on marine organisms in several ways[205,206](Table 5-2). While understanding the physiological impacts of CO_2 is important when assessing the potential survival or mortality of individuals or species, it is also important to consider whether species loss will also lead to reductions in the key ecological or biogeochemical functions needed to maintain a healthy ecosystem. Ecosystem robustness then supports ecosystem services such as climate regulation and food security (Figure 5-2).

It should be noted that rising atmospheric CO_2 over the last century and into the future not only causes ocean warming but also changes carbonate chemistry in a process termed ocean

[205] Secretariat of the Convention on Biological Diversity, 2014, An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity (Eds: S. Hennige, J.M. Roberts and P. Williamson). Montreal, Technical Series No. 75, 99 pages.

[206] Widdicombe, S., Blackford, J.C., Spicer, J.I., 2013. Assessing the environmental consequences of CO_2 leakage from geological CCS: generating evidence to support environmental risk assessment. Mar. Pollut. Bull. 73, 399–401.

acidification. This acidification will affect marine ecosystems for centuries if emissions continue.[207] Considerable amounts of biological data that can be utilized in CCS leakage assessments are available from ocean acidification studies.

Table 5-2 Direct biological impacts associated with high CO_2 conditions in seawater

Direct impacts on:	Description
Growth and survival	Reduction of growth and survival is apparent especially for corals, mollusks and echinoderms. However, the responses are variable, and some species can tolerate substantial high CO_2 conditions.
Acid-base regulation and metabolism	Organisms may need extra energy to maintain their internal acid-base balance when external hydrogen ion levels substantially increase. This can lead to reduced growth and fitness.
Fertilization	Fertilization of some species is highly sensitive to high CO_2 conditions, whilst others are tolerant. Intra-specific variability indicates the scope for a multigenerational, evolutionary response.
Calcification	Early life stages of many of calcifying organisms seem to be particularly sensitive to high CO_2 conditions, with impacts including decreased larval size, reduced morphological complexity, and decreased calcification.
Sensory system and behavior	Some fish and invertebrates show loss of ability to discriminate between important chemical cues. This may lead to behavioral alteration important for their reproduction process.
Photosynthesis	Many macroalgae, seagrass, phytoplankton species can show increased photosynthesis and growth under high CO_2 conditions. Calcifying macroalgae and phytoplankton are, however, negatively impacted.

5.2.1 Analytical tools for seawater CO_2 monitoring

There are four parameters that can be reliably measured for the seawater CO_2 system, namely total dissolved inorganic carbon (DIC), total alkalinity (AT), pH and partial pressure of CO_2 that is in

[207] Pörtner, H.-O., Karl, D.M., Boyd, P.W., Cheung, W.W.L., Lluch-Cota, S.E., Nojiri, Y., Schmidt, D.N., Zavialov, P.O., 2014: Ocean systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

equilibrium with a water sample (pCO_2).[208] It is possible to obtain a complete description of the acid-base composition of a seawater sample at a particular temperature and pressure provided the following are known:

- The salinity and temperature, and hence the solubility constant of CO_2 in the seawater as well as the equilibrium constant for each of the acid dissociation reactions that is assumed to exist in the solution;
- The total concentrations for each of these non-CO_2 acid-base systems;
- The values for at least two of the CO_2-related parameters: DIC, AT, pH, pCO_2.

Measurement of a combination of DIC and AT can be recommended for the most accurate monitoring on natural seawater as samples for these can be preserved easily and the measurements made with low uncertainty. As an alternative, combination of pH and DIC is also recommended. However it should be noted that the calculated CO_2 system parameters are typically dominated by the uncertainty in the pH measurement.

For the calculation of seawater CO_2 system including saturation states (Ω) of $CaCO_3$ the most acknowledged program is CO2SYS[209] which is available at http://cdiac.ornl.gov/oceans/co2rprt.html.

Practical technology for marine and seabed monitoring is in Chapter 7.

5.2.2 Simulation tools for leakage scenarios

There is no dissimilarity in simulation tools for leakage from reservoir to surface between onshore and offshore. The final key element in understanding potential consequence of CO_2 leakage is to understand the sea area impacted by harmful high CO_2 conditions for given leakage scenarios. It is useful to model hypothetical leakage scenarios for estimating potentially impacted areas. If deleterious impacts are spatially restricted then environmental concerns diminish and vice versa.

Once leakage rates at the seafloor are given by leakage simulations in subsea geological formations, CO_2 fate in seawater can be predicted by numerical simulations. Leaked CO_2 can occur in both gas and dissolved phases when it seeps out from the seafloor. The bubble CO_2 rises in the water column forming bubble plumes and rapidly dissolves into the seawater during its ascent.

[208] European commission, 2010, EUR 24328 – Guide to best practices for ocean acidification research and data reporting. Luxembourg: Publications Office of European Union, 260pp.

[209] Pierrot, D., Lewis E., Wallace D.W.R., 2006. MS Excel Program Developed for CO_2 System Calculations. ORNL/CDIAC-105a. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. http://dx.doi.org/10.3334/CDIAC/otg.CO2SYS_XLS_CDIAC105a.

Dissolved CO_2 disperses in the sea by water currents and tidal mixing. The sequence of CO_2 dispersion in the sea have been modeled in detail to predict the impacted area.[210,211,212]

5.3 R&D Opportunities and recommendations

Over the last decade or so a significant body of research into the impacts of high CO_2 on marine systems has matured, driven directly by CCS but also by concerns regarding ocean acidification. Much of this work has concentrated on physiological impacts and has utilized laboratory scale manipulations. However both natural analogues, typically where volcanic CO_2 is emitted at the seafloor,[213] and more recently a controlled release experiment, where CO_2 was deliberately injected into the seabed,[214] have been used to study the synergistic impacts driven by a combination of hydrodynamics, ecosystem interactions, behavior and physiological responses. These systems also provide highly realistic environments in which to test a variety of monitoring tools and strategies (q.v. Marine and seabed monitoring, Chapter 7.2 Offshore Monitoring Technology) and are very well suited to communicating realistic impact scenarios to concerned parties including the general public. The main outcome from these real world experiments is a glimpse of the complexity of impacts and the challenges to efficient monitoring, in particular the requirement for a comprehensive understanding of natural variability necessary to correctly identify and quantify non-natural change. Natural analogue sites are geographically diffuse, and due to their volcanic nature never associated with candidate storage sites and controlled release experiments are expensive to develop. Nevertheless the knowledge gain is so significant that more such experiments, in diverse storage sites can only be recommended. Specific challenges arising from existing work are to understand the buffering potential of sediments, and the impact of longer term exposures. In the short term it has been observed that carbonates, naturally present in some sediments undergo dissolution in the presence of excess CO_2, reducing the presence of gas at the seafloor, some of the chemical parameters and biological impacts. However sediment carbonate is finite and once exhausted a step change in detectability and impact is likely.

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[210] Mori, C., Sato, T., Kano, Y., Oyama, H., Aleynik, D., Tsumune, D., Maeda, Y., 2015. Numerical study of the fate of CO_2 purposefully injected into the sediment and seeping from seafloor in Ardmucknish Bay. Int. J. Greenhouse Gas Control, http://dx.doi.org/10.1016/j.ijggc.2014.11.023

[211] Sellami, N., Dewar, M., Stahl, H., Chen, B., 2015. Dynamics of rising CO_2 bubble plumes in the QICS field experiment Part 1 – The experiment. Int. J. Greenhouse Gas Control, http://dx.doi.org/10.1016/j.ijggc.2015.02.011

[212] Dewar, M., Sellami, N., Chen, B., 2014. Dyanamics of rising CO_2 bubble plumes in the QICS field experiment Part 2 – Modelling. Int. J. Greenhouse Gas Control, http://dx.doi.org/10.1016/j.ijggc.2014.11.003

[213] Caramanna, G., Voltattorni, N. and Maroto-Valer, M. M. (2011), Is Panarea Island (Italy) a valid and cost-effective natural laboratory for the development of detection and monitoring techniques for submarine CO_2 seepage?. Greenhouse Gas Sci Technol, 1: 200–210. doi: 10.1002/ghg.28

[214] Blackford, JC; Stahl, H; Bull, JM; Bergès, BJP; Cevatoglu, M; Lichtschlag, A; Connelly, DP; James, RH; Kita, J; Long, D; Naylor, M; Shitashima, K; Smith, D; Taylor, P; Wright, I; Akhurst, M; Chen, B; Gernon, TM; Hauton, C; Hayashi, M; Kaieda, H; Leighton, TG; Sato, T; Sayer, MDJ; Suzumura, M; Tait, K; Vardy, ME; White, PR; Widdicombe, S. 2014. Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage. *Nature Climate Change* 4, 1011-1016. DOI: 10.1038/NCLIMATE2381

Models of hydrodynamics or bubble plume behavior, often coupled with CO_2 speciation equations have been used to address a wide range of leakage scenarios.[9,11,215] Whilst the primary driver of the spatial extent of detectability and impact is the leakage rate, many other factors such as depth, bubble size, current speed, tidal mixing and topography are shown to have a large influence on dispersal. Whilst these existing models are robust, they are limited in that they generally cannot deal with very fine scales (≈1m), necessary for the correct treatment of small leak scenarios at the same time as accurately defining regional scale mixing processes, necessary for the correct estimation of dispersion. Further these models do not simultaneously deliver detailed estimates of natural variability of carbonate chemistry, as driven by biological processes, with leakage predictions. Models that aspire to such a multi-scalar multi-process functionality are under development, limited mainly by computational demands, rather than fundamental lack of understanding. The existing modelling provides clear evidence that no two leakage scenarios are alike and a recommendation for any storage site is to commission a bespoke model analysis to inform both the range of potential leakage extents and the potential variability in the natural environment.

The majority of work to date has focused on the detectability and impacts of high CO_2 reaching the seafloor including the mobilization of other chemical species under low pH conditions. A scenario that has not been adequately investigated is the potential for hyper-saline anoxic formation water expulsion as a precursor at storage complexes situated in saline aquifers. Natural analogues or even controlled release experiments addressing this phenomenon would be a potentially valuable addition to the research base, presuming that expulsion of formation water is geologically realistic.[216]

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[215] Phelps, J.J.C, Blackford, J.C., Holt, J.T., Polton, J.A. Modelling Large-Scale CO_2 Leakages in the North Sea. Int J Greenhouse Gas Control, (in press). doi:10.1016/j.ijggc.2014.10.013

[216] Hannis S., Bricker S., Goater A., Holloway S., Rushton J., Williams G., Williams J. Cross-international Boundary Effects of CO_2 Injection**.** *Energy Procedia*, *Volume 37*, *2013*, *Pages 4927-4936*

6 Wellbore management

6.1 Well construction technologies

The construction of an offshore well can be divided into a five main phases:

1) Planning
2) Drilling
3) Completion and commissioning
4) Operation
5) Plug and abandon

6.1.1 Pre-drilling activities

The main planning activities consist of:

- Identifying reservoir targets and possible infrastructure locations
- Site investigation
- Detailed well and facilities planning (drilling, completion and commissioning)
- Well risk assessment and mitigation planning

An important part of the site investigation is the identification of potential hazards. The geohazard assessment is recommended for every well drilled. The shallow hazards evaluation should contain the following.

- Shallow Gas Classification
- Shallow water flow
- Soil stability issues such as landslides
- Depth to all interpreted formations
- structural closures
- Faults
- Shallow sediments
- Anchoring conditions
- Boulders
- Neighboring well geohazards

Furthermore, for the geotechnical investigation a shallow gas interpretation needs to be available prior to execution of geotechnical investigations.

Important planning aspects when constructing an injection well:

- The pressure operational window needs to be set early in the planning stage to ensure sufficient design parameters, i.e., minimum and maximum pressures and temperatures, formation strength, formation fluid types and salinities, etc.
- Drilling fluids: One of the main purposes of the drilling mud is to remove drill cuttings from the hole by keeping the particles in suspension. Another main function is to control the formation pressure, at the same time as it must not cause damage to the formation by reducing its injectivity.
- Ensure hydraulic isolation between formation and all casing strings
- Instrumentation should be installed to detect any potential future leaks.
    - Bottom-hole pressure and temperature
    - Wellhead pressure and temperature
    - Fluid injection rate
    - Annulus pressures

Sensors can be used to monitor pressures and temperatures outside the casing

A shallow gas pilot may need to be drilled if shallow gas is a potential concern. The shallow gas pilot well is typically drilled to 800-1000 m.

6.1.2 Drilling phase

For carbon storage there are three types of wells: characterization (or exploration), injection, and monitoring wells. Characterization wells are used to evaluate the site suitability for safe carbon storage, mainly focused on reservoir and caprock properties. Utilizing existing data from oil exploration wells can greatly decrease the need for characterization wells. Injection wells are drilled to be used in disposal operations. The wells are optimally located for injection technical reasons. While production wells in an oil reservoir are drilled in the oil zone, injection wells are usually drilled to a gas or water zone, and only exceptionally in the oil zone. Monitoring wells are used strictly to monitor the CO_2 plume and the effect it is having on the subsurface.

In order to be usable from a central platform, injection wells are generally deviated wells. Wells added to existing infrastructure are drilled from fixed installations. However, subsea-completed wells and pre-drilled wells are drilled from floating facilities or jack-up platforms.

Offshore wells are often drilled with small pressure margins and advanced techniques. These margins mean that drilling operators are challenged to keep pressures across the entire well high enough to avoid formation collapse while not exceeding the formation fracturing pressures.

Drilling and well operations are high risk activities with regards to safety, environmental and economic exposure. The activities involve cooperation between many participating parties, work with over-pressured formations that may contain hydrocarbons, and use highly specialised equipment. The ultimate risk is uncontrolled hydrocarbon flow with the possible loss of life, damage to property and environment and subsequent harm to the company's reputation.

A typical injection well is first spudded (drilled) using a 36"-hole opener. If the seabed is soft or uneven, a temporary guide base is installed on the seabed. The 36" holes are typically drilled to around 60-80 metres under the seabed. Seawater is used to circulate out sand and silt, which flow onto the seabed. The hole is filled with a viscous liquid which prevents it from collapsing before the drillstring is retracted. Afterwards, a 30" conductor casing is run through a permanent guide base and run in the hole. The casing functions to prevent the hole from collapsing and prevents contamination of the ground water in the upper formations. The conductor casing is then cemented to the formation all the way up to the seafloor.

Subsequently, the drilling of a 26" hole often commences without risers. Return of the drill cuttings is to the seabed. When drilling on a subsea template using several slots, the drill cuttings are moved 50-100 metres away. In some cases of pre-drilling of wells, the 26" holes are drilled with risers to circulate drill cuttings back to the rig. A pilot hole can be drilled if shallow gas is considered an issue. A blow-out preventer is often not used, only a diverter valve at the top, and the drilling fluid is seawater with a little added weighting material to obtain a density of approximately 1.1g/cc. A likely depth for 26" holes is in the region of 400- 500 metres below the seabed, but this depends on geological conditions and well target depth. Then a 20" surface casing is run. Normally, the 20" surface casing is cemented up to the surface (seabed). After the wellhead is in place, a blowout preventer is used for all subsequent drilling operations. The blowout preventer is connected to the top of the wellhead.

After the 20" casing is in place, a 17½" hole is usually drilled using a blowout preventer and risers. The blowout preventer comprises a system of valves on top of the wellhead. Its function is to secure the well in the event that downhole fluids start flowing into the well due to a high-pressure zone, or if the drilling mud is too light. After the 17 ½" holes is drilled 13 3/8" casing is run and cemented. The casings is cemented above all permeable zones, or in many cases, up to the 20'' casing.

Afterwards, drilling is carried out using a 12¼" bit. This section is often drilled to just above the reservoir. In some cases, this section is drilled through the reservoir. The 12¼" hole is usually cased with 9 5/8" casing and cemented up to the previous casing string. The cement is required to be above the proposed packer depth and verified by logs. Hydraulic isolation is essential for ensuring outer well integrity. This is especially important in injection well operations.

If the 12¼" hole is not drilled through the reservoir, an 8½" bit is used for drilling through the reservoir. The hole is cased with a 7" casing. This is often suspended from the lower part of a 9 5/8" casing, but sometimes run in all the way up to the surface. It is particularly important to cement this section, as a leak could result in fluids rising to the surface through migration up the annulus.

Characterization wells are drilled to gather detailed information on the reservoirs and caprocks. Much of the time they are not designed for any other use, and are plugged and abandoned after the information is gathered. The data is gathered by taking many meters of formation core, running multiple logging suites, and performing fluid injection or extraction tests. Although the well design can be simpler due to the lack of the final string of casing, there is usually a lack of experience drilling in the area and thus protections need to be put in place to mitigate the risk of unanticipated hydrocarbon accumulations, higher than expected pressures, or other geohazards.

Since monitor wells do not need to allow for fluid to be pumped through them, they can usually be designed for smaller diameters. The size will depend on the technologies to be deployed in or through them. If there will not be perforations through the casing, there is no need to run a packer and tubing. Technologies can be run outside of the casing, between the casing and tubing, and on wireline inside the tubing. These technologies are discussed in detail in the next chapter.

6.1.3 Well completion and commissioning

Completion involves running in the tubing, installing monitoring equipment, packers, liner/tubing hanger systems, valves and tree. Any string, including all connections and down-hole equipment, should be of such diameter, wall thickness, material quality and strength, and installed in such a manner, that it will withstand the structural and pressure restraining loads.

The completion can be divided into the lower and upper completion.

<u>The lower completion</u> refers to the portion of the well across the injection zone in the reservoir. Typically, the lower completion is set across the reservoir using a liner hanger system, which anchors the lower completion to the casing string. Several types of lower completion designs have been used for injection wells i.e., open hole, cemented and perforated liner, predrilled liner and screens. The recommended lower completion design will depend on factor like formation properties (formation stability, porosity/permeability) and type of fluid to be injected. Formations with low strength and good porosity and permeability should consider using screens unless a lot of particles will be injected.

<u>The upper completion</u> refers to all components from the bottom of the <u>injection tubing</u> upwards.

The tubing provides isolation of fluids and pressures from the casing, well control, injection control, stimulation control, and a retrievable “replaceable” pipeline to the reservoir. When selecting the tubing it is necessary to evaluate material quality relative to the planned use (strength and corrosion). For CO_2 injectors where the fluid can be corrosive, 13Cr or better should be considered. This material selection will also depend on the desired lifetime. The tubing should have a size that enable sufficient flow and allow for anticipated tool passage during future workovers or logging operations.

All offshore wells should have a subsurface safety valve installed in the tubing below the level of the seafloor. These valves, whether surface- or subsurface-controlled, operate in a failsafe mode, meaning in any upset condition they automatically close, sealing off all vertical flow in the well.

Placement of the packer is critical for safe injection operations. A leak above the packer will be detected on the annulus pressure. A leak below the packer can be more difficult to detect. The packer should also be placed in well-cemented casing.

The well can be perforated either before, during, or after the lower and upper completions are run.

Well commissioning takes the completed well and prepared it to accept the injection fluid (CO_2). It consists of two tasks:

1. Connecting and verifying the accuracy of all instrumentation
2. Placing the proper fluid in the wellbore.

After the completion of the injector wells, there is a possibility that the wells will not have been cleaned up sufficiently. A remedial action will often be required to decrease the skin damage on the well. A breaker is then often spotted across the reservoir section, which should dissolve the filter cake built up during the drilling of that section. However there is the possibility that the wells may not clean up sufficiently and then conventional coiled tubing will be required to carry out remedial action to decrease the skin damage on the well.

When CO_2 injection starts whatever fluid is in the wellbore will be pushed ahead of the injectate and into the reservoir. Some formations, due to their mineralogy, are easily damaged by water, the wrong salinity of water, or the presence of certain chemicals in the fluid. In some cases the well will need to be circulated and pressurized with CO_2 in order to not damage the reservoir at the initiation of injection.

6.1.4 Well operation

During the injection operations key parameters are continuously or periodically monitored to ensure no damage to the well, reservoir, or caprock. Alarm points are set for these parameters and mitigation actions are pre-determined for each scenario. Since the well is downstream of the pumps and pipeline, and problems with the well could cause damage to all equipment upstream of it, the monitoring of the well operation should be performed by the same control room as the pipeline, which will most probably be onshore.

Common measurements made include:

- Injection well downhole pressure and temperature
- Injection well surface pressure and temperature
- Injection well tubing/casing annular pressure
- Injection well flow rate
- Monitoring well in-zone pressure
- Above-caprock formation pressure (injection well, monitoring wells, or both)
- Microseismic activity (from any well or permenent ocean-bottom sensor)
- Time-lapse logs in all wells

Most of the mitigation actions would require mobilization of equipment and/or a rig to the site, thus causing a delay in remediation, and could also be quite expensive to perform. Thus offshore storage demands that the wells be engineered to be operable under as many conditions as economically possible in order to minimize the number of interventions.

6.1.5 Plug and Abandonment

The proper procedures for P&A of all wells will be specified by the regulatory agency. Specific to carbon storage wells will be the requirement that plugging materials be resistant to carbonic acid. Multiple plugs will be required in each well to ensure permanent sealing of the well. Since the injection interval will probably be at a much higher pressure than it was originally, extra care will need to be taken to guarantee well control during the entire plugging operation.

6.2 Wellbore Construction Materials and Integrity

The basis for injection wells is designing a fit for purpose well ensuring safe and effective injection of the planned fluids. The injection well also needs to be equipped with instrumentation enabling sufficient monitoring.

Considerations within the well design and monitoring include:

1. *Well design* and construction materials are site specific and will depend on factors such as:

- local geological setting (depth, fluid chemistry, pressure, temperature)
- expected design life of the injection well
- injection and reservoir fluid characteristics
- formation chemistry
- injected fluid chemistry
- Pressure (formation and injected fluid)
- Temperature (formation and injected fluid)
- injection rates

2. *Material quality:* Material selection for CO_2 injection requires input related to physical and chemical composition of reservoir an injected fluid in addition to pressure and temperature the well will be exposed to during the well lifetime. Additionally, there are various materials that are part of a well, including cement and polymers/rubbers. For CO_2 injectors the liner and liner hanger system should be corrosion resistant material such as 13CrS110 material to resist corrosion. The parts in the lower completion contact with formation water should also be corrosion-resistant material.

Under standard atmospheric conditions CO_2 is always in the gas state. For pressure above 73 bar and 31 °C the CO_2 goes into single phase—supercritical phase. For some rubbers the supercritical phase has been shown to influence more than pure gas exposure. The main effects of CO_2 in gas and liquid form on rubbers are:[217]

- Physical swelling—with associated loss in mechanical properties.

[217] Reidar Stokke, CO2PIPETRANS – Technical study: Material compatibility for polymers and elastomers,2008-12-01, SINTEF Report

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- Explosive decompression (ED)—dissolved gas trapped in rubber that expands when the pressure drops.
- Chemical degradation

It was concluded that the chemical degradation from CO_2 on its own is minimal for the standard oilfield rubbers.[218] From the literature[218] it seems that the two main parameters for a successful use of rubbers are:

- The rubbers should show minimal swelling (at operating conditions).
- The resistance to explosive decompression should be good minimal for the standard oilfield rubbers. The main challenge with CO_2 exposure is the ED damage.

Rubber quality should be evaluated in relation to dynamic, static and shear ram seal of the BOP and other critical components in the well.

3. *Injection pressures* should not be higher than the fracture closure at the packer setting depth. The reason for this is that a leaking casing below the packer will not be detected on annulus pressure.

4. *The cement* must provide hydraulic isolation above the target reservoir to prevent out of zone injection.

5. *Well Instrumentation needs.* Instrumentation is of critical importance ensuring optimal and safe injection operations. Chapter 7 on monitoring technologies provides more details, but the importance of well instrumentation needs are defined below.

- Injection pressures operating within predefined operating window based on topside design, well design and formation limitations.
- Early detection and stop of injection with abnormal well behaviour
- Use of high and low alarms defined by well design and formation limitations in the operations phase enabling detection of abnormal well behavior.
- Annulus pressures monitoring to detect leaks in injection tubing and annulus monitoring to detect abnormal pressure buildup in formation outside casing that can be caused by out of zone injection (OOZI). Leaks into overburden can significantly increase the P&A cost when permeable overpressured zones need to be isolated.

6.3 Well Remediation

Well remediation can take many forms depending on the problem being corrected. In the offshore environment mobilization to the well can take quite a bit of time, and working space at the well is at a premium. So any remediation will take careful planning and close coordination.

[218] Morris Roseman, Rod Martin, Developing new elastomers from compound to downhole tool demonstrator for steam, supercritical CO_2, and H_2S injection for enhanced oil recovery, Merl Ltd., Wilbury Way, Hitchin, Hertfordshire, SG4 0TW, *MERL Oilfield Engineering with Polymers 2010 20-22 September 2010 – London, UK*

The easiest treatment is when a fluid is pumped down the well to dissolve some kind of blockage. Typical problems could be scale plugging the tubing or perforations, fines plugging the sandface, or hydrates in the interval from the wellhead to the mudline. Diagnosing these problems to select the correct fluid can be the hardest part, and many times require the mobilization of a wireline or slickline unit to run measurements inside the well. In some cases the wireline unit can fix the problem itself by adding perforations, spotting fluid with a bailer, shifting a sliding sleeve, setting a plug, or many other tasks.

If these methods do not work, the next level of effort requires a coiled tubing unit to be mobilized to the well to spool a continuous tube down the inside of the well. The many potential usages include using a drill bit and motor to drill out a blockage, a jetting tool to cut scale off the sides, a grapple or bailer to fish debris out of the well, various downhole assemblies to spot chemicals at specific points in the well, or squeezing cement or other sealants into leaks. Again, diagnosing the problem could include the use of other techniques such as wireline or slickline.

If the tubing and/or packer needs to be removed from the well, a workover unit or rig will need to be mobilized. The type of rig will depend on the type of well being remediated. It could vary from a small unit on a barge, a platform rig, a jackup, or a semisubmersible. The uses would be to replace a joint of tubing or leaking packer, squeeze a hole in the casing, replace downhole hardware, or recomplete the well in another interval.

Well remediation is a complex process that requires close cooperation among many disciplines. Installed hardware does not always come free as designed. Squeeze jobs do not always plug the leak. The organization needs to be nimble enough to react to unforeseen results by changing the remediation plan on the fly. Thorough brainstorming of possible scenarios and mitigation actions will pay off in less surprises and reduced down time. This will keep cost to a minimum while enabling the highest odds of success.

6.4 Technical Challenges or Technology Gaps

Offshore wells that receive CO_2 from a subsea pipeline will have much colder temperatures through the wellhead and the shallow sections of the well than any experience in the oilfield. It is poorly understood what effect this will have on well integrity and material durability.

Modeling has shown that an uncontrolled CO_2 blowout (such as the wellhead getting knocked off by a ship) could cause extremely low temperatures in a shallow-set subsurface safety valve. It is not yet demonstrated that the metallurgy and response systems could withstand these low temperatures.

When cold CO_2 from a subsea pipeline is injected into a depleted offshore field, especially a shallow one, the reservoir may not present enough backpressure to the wellhead and pipeline to keep the fluid in dense phase. Pure CO_2 at 5 °C will boil when the pressure drops below 600 psia. We do not know what effect this will have on the stability of the flow and the ability of the elastomers to maintain their sealing properties.

CO_2 sequestration wells will need to be permanently plugged with material guaranteed to last. Normal well plugging materials are susceptible to degradation by carbonic acid. Unlike onshore wells, plugged offshore wells are very hard to re-enter if they develop a leak.

6.5 R&D Opportunities

Research is needed for materials and procedures that are used to construct, complete, monitor, and plug carbon storage wells. With the high cost of offshore well intervention the long-term durability of metals, elastomers, and electronics will be critical.

The materials used and how they are assembled to combat any negative effects from cold CO_2 entering a wellhead.

- Verify that subsurface safety valves will perform in worst-case scenarios
- Develop probes and electronics that enable accurate monitoring for decades
- Develop well plugging materials that do not degrade when exposed to carbonic acid
- Understand the surface and system implications of injecting into low-pressure reservoirs

As was discussed in Section 4.5, (R&D Opportunities for Transportation, dynamic flow models) for wells also suffer from poor understanding of phase equilibria and equations of state in CO_2 mixtures with small amounts of impurities. Transient flow models require a much better understanding of these conditions in order to accurately predict the conditions wells will be subjected to. Fluid viscosities could swing wildly if trying to operate near phase transition boundaries, as at present small amounts of impurities can cause the equations of state to become unstable.

6.6 Recommendations

Safe and dependable offshore CO_2 sequestration wells will depend on proper data gathering (characterization) and risk management. While the costs will be higher than onshore sequestration fields, it may be much easier to permit and operate. Care will need to be taken to fully evaluate the economics through the entire CCS system so that proper decisions can be made on site selection, CO_2 cleanup, material selection, and monitoring activities. The design and operation of the wells will be very site specific. The above technology gaps and R&D areas could greatly reduce the uncertainties, risks and costs associated with offshore storage.

7 Monitoring, verification and assessment tools for offshore storage

7.1 Offshore monitoring overview

7.1.1 Context

In this chapter we review the current status of technology and methods for monitoring, verification, and accounting (MVA) for offshore CO_2 storage. We focus on summarizing recent experience and identifying important lessons learned for the offshore context. CO_2 storage monitoring and approaches for MVA have been widely addressed in previous reports.[219,220] More recently the IEAGHG[221] has reviewed offshore monitoring for CCS projects and main of the key conclusions from the IEAGHG report are also summarized in this chapter.

7.1.2 The offshore setting

Offshore CO_2 storage is attractive given the large estimated storage capacity, reduced risks to protected groundwater resources and population centers, generally simpler storage resource ownership aspects, and proximity to sources of large industrial CO_2 emissions. The offshore settings also allow for efficient collection of continuous 3D subsurface seismic imaging data over prospective storage sites which can be used for characterization and monitoring.

Monitoring for offshore CO_2 storage has some general characteristics which makes it distinct from monitoring onshore projects. The main differences are that:

- Wells and well interventions are more expensive offshore;
- Geophysical surveys are generally less expensive and often give much better imaging quality;
- The regulatory requirements differ in several respects;
- The marine ecosystem is quite different from the onshore surface environment.

Monitoring for offshore CO_2 storage is quite a mature technology, having been applied since the start of the first industrial-scale CCS project at Sleipner,[222] offshore Norway, in 1996. Since then similar approaches have been applied at the Snøhvit site[223] in the Norwegian Barents Sea (since 2008), at the K12-B pilot site offshore Netherlands (since 2004) and at the Tomakomai CCS

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[219] NETL, 2012. Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations 2012 Update, DOE/NETL-2012/1568 Report, October 2012.

[220] Cooper, C. (Ed.), 2009. A technical basis for CO_2 storage. CO_2 Capture Project, CPL Press, UK. www.co2captureproject.org

[221] IEAGHG, 2016. Offshore Monitoring for CCS Projects, Report 2015/02, May 2015.

[222] Arts, R.J., Chadwick, A., Eiken, O., Thibeau, S., Nooner, S., [2008] Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway. *First Break* 26(1), 65-72.

[223] Hansen, O., Gilding, D., Nazarian, B., Osdal, B., Ringrose, P., Kristoffersen, J-B., Eiken, O., Hansen, H., [2012] Snøhvit: The history of injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm. Energy Procedia, 37, 3565 – 357.

Demonstration Project[224] in Japan (under construction, to be operational in 2016). Two planned offshore CO_2 storage projects at Peterhead-Goldeneye (UK) and ROAD (Netherlands) have also performed extensive scoping studies for offshore monitoring. Figure 7-1 and Table 7-1 summarize monitoring technologies deployed at offshore CO_2 storage site to date.

Time-lapse 3D seismic monitoring has proven to be a highly valuable tool in the offshore setting, with repeat survey intervals of 2–3 years being applied at Sleipner and Snøhvit giving excellent plume monitoring capabilities.[225] The Sleipner project has also successfully applied time-lapse gravity monitoring [226] (Alnes et al. 2011) and tested the potential for controlled source electromagnetic monitoring (CSEM).[227] At the Snøhvit CO_2 storage project, permanent down-hole pressure and temperature gauges were deployed demonstrating the value of downhole gauges in understanding pressure development. Down-hole gauges have also been successfully tested at the K12-B project, where the use of tracers has also been successfully tested, demonstrating their value in understanding CO_2 storage in an offshore depleted gas field. In Tomakomai, the initial 3D and 2D surveys have been conducted and down-hole pressure and temperature measurements are planned for collection of baseline data in early 2015. Microseismicity and natural earthquakes have been already observed continuously with an ocean bottom cable (OBC) equipped with 72 seismometers and four independent ocean bottom seismometers. The OBC will also be used for future repeated 2D surveys.

Marine and seabed monitoring approaches are generally less mature than reservoir monitoring methods, but the technology is rapidly developing and a range of methods have now been successfully tested and applied in the Sleipner area.

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[224] Tanaka, Y., Abe, M., Sawada, Y., Tanase, D., Ito, T., Kasukawa, T., 2014. Tomakomai CCS Demonstration Project in Japan, 2014 Update, *Energy Procedia* 63, 6111 – 6119

[225] Eiken, O., Ringrose, P., Hermanrud, C., Nazarian, B. and Torp, T., 2011. Lessons Learned from 14 years of CCS Operations: Sleipner, In Salah and Snøhvit. 10th International Conference on Greenhouse Gas Technologies. *Energy Procedia,* Volume 4, 5541-5548.

[226] Alnes, H, Eiken, O., Nooner, S., Sasagawa, G., [2011] Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO2 plume. *Energy Procedia* 4, 5505-5511.

[227] Park, J. Vanneste, M. Waarum, I. K., Sparrevik, P. M. and Sauvin, G., 2014, In Situ Resistivity of CO_2 Plume at Sleipner from CSEM and Gravity Data, Near Surface Geoscience 2014 - First Applied Shallow Marine Geophysics Conference

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Table 7-1 Summary of offshore monitoring technologies applied at offshore CO_2 storage projects to date

Monitoring Technology	Sleipner	Snøhvit	K12-B	Tomakomai
High-resolution 2D seismic	*	*		*
Time-lapse 3D seismic	*	*		*
Gravity surveys	* (4D)	* (4D)		* (continuous)
CSEM	*			
Seabed surveys and marine monitoring	*			*
Permanent down-hole gauges		*		*
Tracers			*	
Downhole well-testing during operations		*	*	
Wellbore integrity monitoring		*	*	*
Downhole fluid sampling	*	*	*	
Wellhead monitoring	*	*	*	*

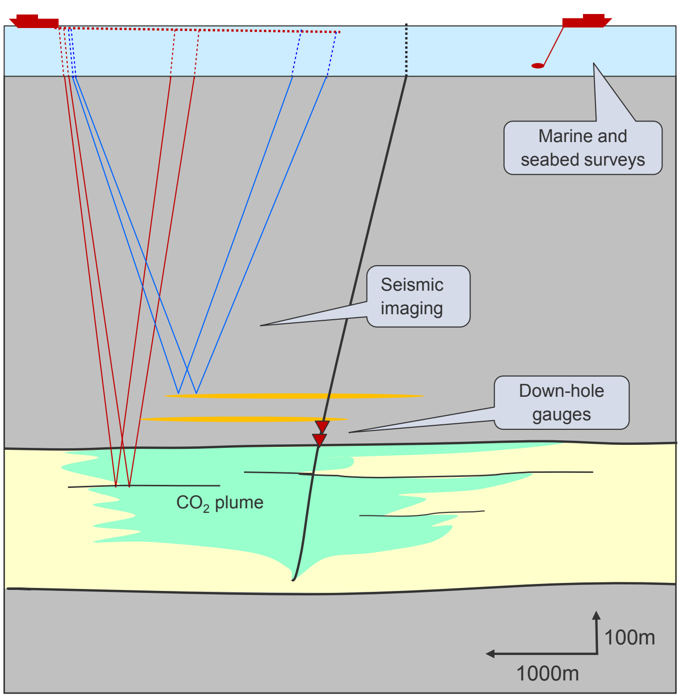

Figure 7-1 Overview of monitoring technologies applied at offshore CO_2 storage projects

7.1.3 Offshore regulation and monitoring objectives

The first overall question for CO_2 storage monitoring is what type of monitoring is needed? There are two aspects to this question:

a) What monitoring is required from a regulatory perspective?

b) What monitoring is cost-effective from an operational point of view?

The regulatory requirements are the overriding factor, but generally leave room for choice and optimization depending on the site context. The operational perspective is therefore often critical as it involves specific choices of technologies and survey intervals that are necessary to achieve certain MVA objectives.

There are two key over-arching regulations that cover offshore CO_2 storage, as reviewed by the recent IEAGHG Report,[228] the London Protocol and the OSPAR Convention. The London Protocol, which is a global agreement to protect the marine environment by regulating waste disposal at sea, was amended in 2006 to include CO_2 storage. Both of these conventions have similar two-stage monitoring guidelines. The first stage covers the performance of monitoring of CO_2 within storage formations and the second deals with the environmental impact in the event that leakage is suspected. The implications are that impacts on the seafloor and marine communities need to be ascertained.

It is in Europe that the regulatory framework is most mature but offshore storage regulations also exist and are developing elsewhere, notably in Japan, Australia and the Unites States. Although drafted at differing levels of detail, the regulatory documents from the different national jurisdictions all emphasize the key role of monitoring and the range of objectives it should serve. These can be broadly distilled as demonstrating that the storage site is performing effectively and safely and that it will continue to do so into the future. This approach can therefore be expressed as providing assurance of containment and conformance.

Since 2007 the international regulatory framework has been evolving notably in Europe with the introduction of the European Storage Directive for CO_2 in 2009. These regulations will be particularly pertinent to the planned projects at Peterhead-Goldeneye, White Rose and ROAD. Sleipner, Snøhvit and K12-B predate current EU legislation. The Sleipner and Snøhvit projects were licensed under Petroleum legislation in Norway, but have been used as case studies for informing the EU Directive, which has been recently adopted into Norwegian law. The EC Storage Directive specifically addresses monitoring for the purposes of assessing whether injected CO_2 is behaving as expected, whether any migration or leakage occurs, and if this is damaging the environment or human health.

OSPAR is primarily focused on detecting and avoiding leakage and emissions and therefore identifies the following objectives for a monitoring program:

- Monitoring for performance confirmation;
- Monitoring to detect possible leakages;
- Monitoring of local environmental impacts on ecosystems;
- Monitoring of the effectiveness of CO_2 storage as a greenhouse gas mitigation technology.

The following essential elements of monitoring and control are stated as required to help achieve these objectives:

- The injection rate;
- Continuous pressure monitoring;
- Injectivity and pressure fall-off testing;

[228] IEAGHG, 2016. Offshore Monitoring for CCS Projects, Report 2015/02, May 2015

- The properties of the injected fluid (including temperature and solid content, the presence of incidental associated substances and the phase of the CO_2 stream);
- Mechanical integrity of seals and (abandoned) wells;
- Containment of the CO_2 stream including performance monitoring and monitoring in overlying formations to detect leakage;
- Control measures, overpressure and emergency shutdown system.

It is clear from the wide range of regulatory requirements that have been developed, that regulation has reached different stages of maturity across the world. There are, however, two relatively consistent monitoring-related themes:

a) The requirement to demonstrate that a storage site is performing effectively and safely;

b) The need to ensure that it continues to do so via the provision of information supporting robust prediction of future performance.

These requirements for monitoring offshore storage can be distilled into a number of necessary actions, which fall within two main monitoring objectives: containment assurance and conformance assurance. A third category, contingency monitoring may be required in the event that containment and/or conformance requirements are not met.

In terms of the types of monitoring tools used, it is sometimes convenient to categorize them as deep-focused (providing surveillance of the reservoir and deeper overburden) and shallow-focused (providing surveillance of the near seabed, seabed and water-column) as described in the IEAGHG report[229] and summarized in Table 7-2.

[229] IEAGHG, 2016. Offshore Monitoring for CCS Projects, Report 2015/02, May 2015

		OSPAR	EU Directive	EU ETS	
Deep-focussed monitoring actions	Migration in overburden				Containment
	Containment integrity				Containment
	Migration in reservoir				Conformance
	Performance testing and calibration and identification of irregularities				Conformance
	Calibration for long-term prediction				Conformance
	Testing remedial actions				Contingency
Shallow-focussed monitoring actions	Verification of no leakage				Containment
	Leakage detection				Containment
	Emissions quantification				Contingency
	Environmental impacts				Other
	Testing remedial actions				Contingency

Table 7-2 Objectives for Deep and Shallow-focused monitoring (as proposed by the authors of the IEAGHG report).

7.1.4 Monitoring experience at Sleipner

The Sleipner CO_2 injection project was the world's first offshore industrial CO_2 storage project and emerged at a time when there were no regulations for monitoring CO_2 injection (the project was licensed under Norwegian petroleum regulations). Consequently, the project has served as a full-scale "laboratory" for testing and developing monitoring techniques, being extensively used as a case study in the 2005 IPPC special report on CCS230 and numerous research projects. Figure 7-2 shows an overview of monitoring techniques tested and used at the Sleipner CO_2 injection site.

Seismic 3D monitoring was from the start the main monitoring technique at Sleipner.[231] It has been very successful, despite the fact that the seismic surveys were designed mainly for monitoring the deeper gas condensate production in the area. The main reason for the success is the high porosity of the reservoir, promoting large velocity and density contrasts between the injected CO_2 and the original brine in the pore space. CO_2 at Sleipner is injected close to the base of the Utsira sandstone Formation at an injection point at a depth of 1010 m (TVD MSL). The 200-300 m thick sand-rich Utsira Fm. with porosities of 35-40 percent and permeability values mainly over a Darcy (10^{-12}

[230] Metz, B., Davidson, O., De Coninck, H. C., Loos, M., and Meyer, L. A., 2005. IPCC special report on carbon dioxide capture and storage: Prepared by working group III of the intergovernmental panel on climate change. IPCC, Cambridge University Press: Cambridge, United Kingdom and New York, USA.

[231] Arts, R.J., Chadwick, A., Eiken, O., Thibeau, S., Nooner, S., 2008. Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway. *First Break* 26(1), 65-72.

m^2) provides an excellent storage domain with good capabilities for testing monitoring techniques.[232] Since injection start in 1996, the CO_2 plume has gradually spread laterally and vertically, within a series of stacked sandstone layers separated by thin shale layers, gradually rising to the top Utsira/caprock interface at a depth of around 820 m. The time-lapse seismic observations have provided both containment monitoring (confirming that the CO_2 has not migrated out of the Utsira storage unit), and conformance monitoring (providing a better understanding of the CO_2 flow behavior in the reservoir). Other technologies tested at Sleipner have been time-lapse gravity,[233] seafloor mapping (sonar and echo beam),[234] water and sediment sampling,[235] and a test of the feasibility of monitoring using CSEM.[236]

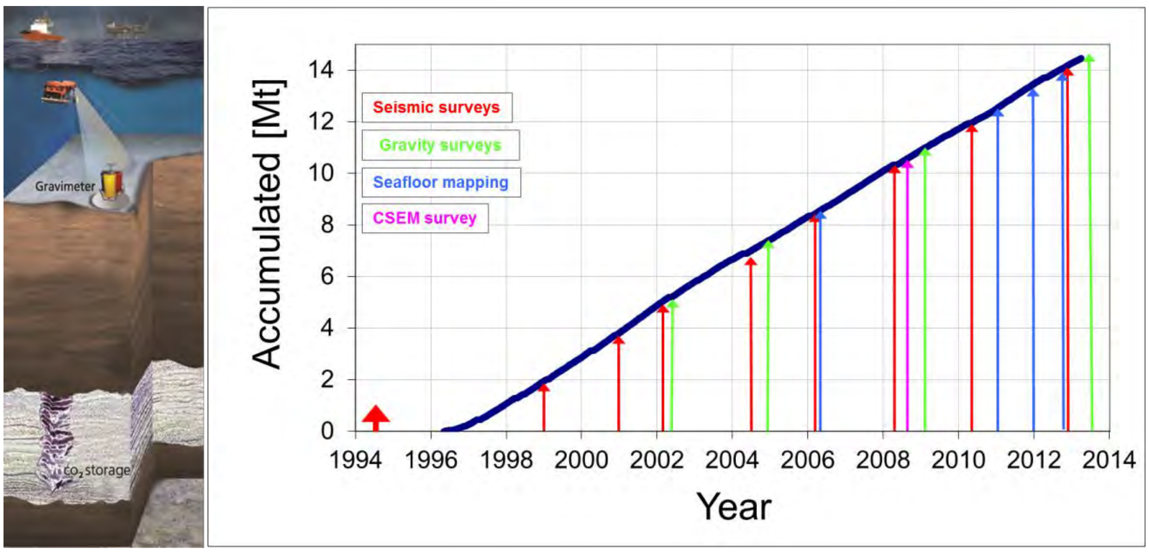

Figure 7-2 Illustration of seismic, gravimetry and sonar measurements at Sleipner (left) and monitoring techniques employed at Sleipner as a function of CO_2 stored (right)

[232] Eiken, O., Ringrose, P., Hermanrud, C., Nazarian, B. and Torp, T., 2011. Lessons Learned from 14 years of CCS Operations: Sleipner, In Salah and Snøhvit. 10th International Conference on Greenhouse Gas Technologies. *Energy Procedia,* Volume 4, 5541-5548.

[233] Alnes, H, Eiken, O., Stenvold, T., 2008, Monitoring gas production and CO_2 injection at the Sleipner field using time-lapse gravimetry. *Geophysics,* 73(6), WA155-WA161.

[234] Linke, P., ed . (2011) RV ALKOR Fahrtbericht / Cruise Report AL374; 29.05.-14.06.2011, Kiel - Kiel; ECO_2 - Sub-seabed CO_2 Storage: Impact on Marine Ecosystems IFM-GEOMAR Report, 51 . IFM-GEOMAR, Kiel, 55 pp. DOI 10.3289/IFM-GEOMAR_REP_51_2011.

[235] Pedersen, R. B. and Reigstad, L. J. and Centre for Geobiology, UiB (2011) Cruise Report GS11B: The Sleipner area, North Sea ; R/V G.O. Sars, Expedition No. 2011108/CGB2011, June 24th– July 1st 2011, Bergen, Norway – Bergen, Norway Centre for Geobiology, UiB, Bergen, Norway, 38 pp. DOI 10.3289/CR_ECO2_20594.

[236] Park, J. Vanneste, M. Waarum, I. K., Sparrevik, P. M. and Sauvin, G., 2014, In Situ Resistivity of CO_2 Plume at Sleipner from CSEM and Gravity Data, Near Surface Geoscience 2014 - First Applied Shallow Marine Geophysics Conference

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In general, the repeat seismic monitoring at Sleipner has proved most valuable, being able to address multiple MMV issues, including the spatial extent of the CO_2 plume, the vertical migration of the plume between sand layers within the Utsira, and the containment of the CO_2 plume beneath the Nordland shale. Gravity field monitoring has also been very valuable as a control on mass distribution, and has provided a constraint on the rate of CO_2 dissolution in brine. The seafloor mapping techniques have been valuable in helping to define how monitoring methods can be applied in the offshore setting.

Routine wellhead monitoring of pressure, temperature and flow rate have confirmed a very stable injection history with the wellhead temperature held at 25°C and the pressure remaining stable at 62-65 bar (close to the gas-liquid phase transition point). Permanent downhole gauges were not deployed at the Sleipner CO_2 injection well.

7.1.5 Monitoring experience at Snøhvit

The Snøhvit CCS project which started CO_2 injection in April 2008, adopted a similar monitoring strategy to Sleipner with a base-line seismic survey acquired in 2003 followed by three repeat seismic surveys so far (in 2009, 2011 and 2012) and a gravity field survey (baseline and 1 repeat so far). Furthermore, the successful deployment of a down-hole pressure and temperature gauge in the injection well proved especially valuable. In 2011 the injection strategy was modified by changing the downhole injection completion, closing off the lower Tubåen Fm. completions and switching to injection in the higher Stø Fm.[237] By the end of 2014 the project had injected 9 Mt CO_2 with a little over 1 Mt having been injected into the Tubåen Fm.

By combining down-hole gauge data with 4D seismic monitoring (Figure 7-3), Snøhvit project was able to optimize the injection strategy in response to operational challenges related to reservoir uncertainties. The expected formation permeabilities around the injection well were in the range of 100mD to 8D. However, analysis of pressure gauge data during the first 3 years of injection showed that the effective permeability away from the wellbore was significantly lower than this, due to the effects of geological barriers. This led to a gradual rise in the injection well pressure, eventually leading to a limit on the injection period as the operational pressure limits was approached (Figure 7-3). Analysis of the first time-lapse seismic survey (2009) also revealed a limited degree of injection into the upper two perforations (Tubåen 2 and 3), with most of the CO_2 being injected into the lowermost perforation (Tubåen 1). These monitoring observations were then used to design a well intervention operation in April 2011—the world's first such operation for a CO_2 injection well from a subsea template.

[237] Hansen, O., Gilding, D., Nazarian, B., Osdal, B., Ringrose, P., Kristoffersen, J-B., Eiken, O., Hansen, H., [2012] Snøhvit: The history of injecting and storing 1 Mt CO2 in the fluvial Tubåen Fm. Energy Procedia, 37, 3565 – 357.

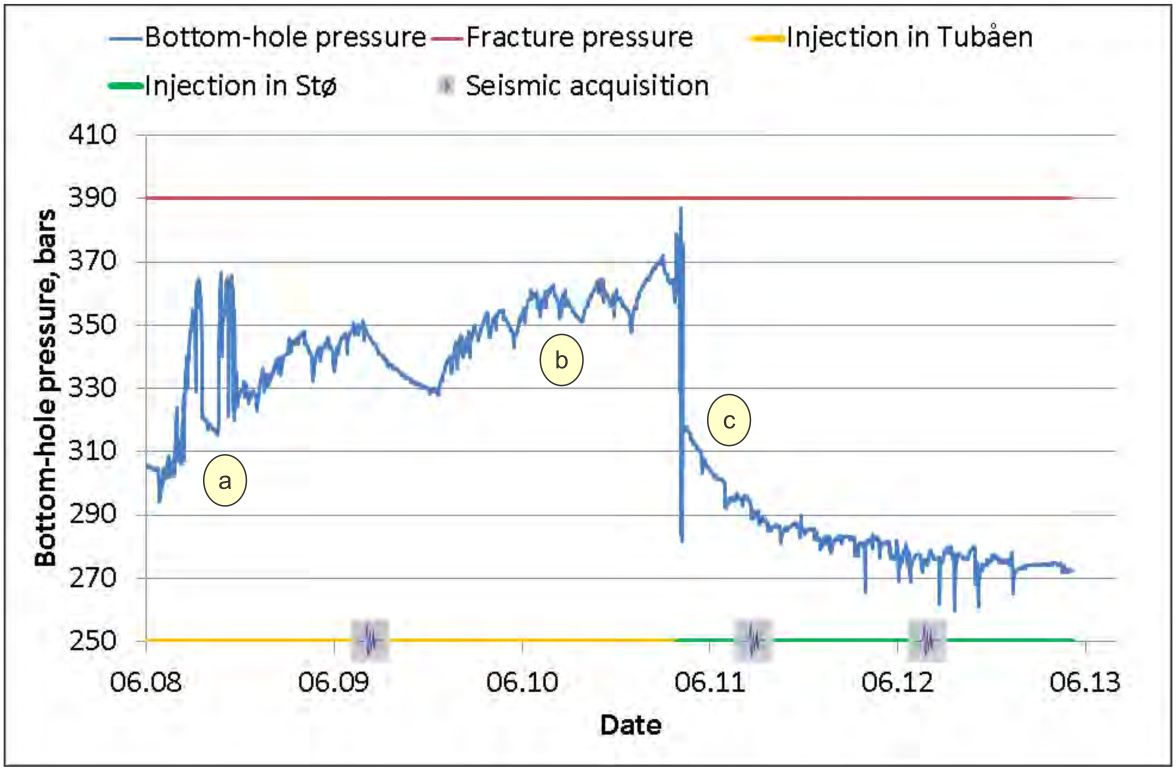

Figure 7-3 Pressure history at the Snøhvit CO_2 storage site (2008 to 2013) with time-lapse seismic acquisition surveys. Three main features of the injection pressure history are: a) early rise in pressure due to near-wellbore effects related to salt drop-out, b) a gradual rising trend in pressure due to geological flow barriers in the Tubåen Fm., and c) pressure decline to a new stable level following diversion of the injection into the overlying Stø Fm.

Following formation testing of the existing CO_2 perforations, the decision was made to deploy a back-up injection solution by isolating the Tubåen interval and switching the injection to the overlying Stø Formation. Subsequent CO_2 injection into the Stø Fm (since 2011) has continued without interruption and with pressure falling to a stable level (Figure 7-3) due to the better lateral continuity of the Stø Fm.[238] It should be noted that this change in the Snøhvit injection plan was within the expected range of uncertainty identified at the start of the project, and that the alternative injection option was deployed using a well designed to be flexible. By combining surface geophysical and downhole monitoring data, the project was able to successfully respond to operational challenges related to geological and reservoir uncertainties. The Snøhvit project is planning a second CO_2 injection well (to be drilled in 2016) as part of the long-term strategy to ensure continued CO_2 storage as part of this large gas development project.

[238] Osdal, B., Zadeh, H. M., Johansen, S., Gonzalez, R. R., and Wærum, G. O., 2014. Snøhvit CO_2 Monitoring Using Well Pressure Measurement and 4D Seismic. Extended abstract presented at Fourth EAGE CO_2 Geological Storage Workshop, 22-24 April 2014, Stavanger, Norway.

7.1.6 Monitoring experience at K12-B

The K12-B gas field is located in the Dutch sector of the North Sea, some 150 km northwest of Amsterdam. Since 2004, produced CO_2 has been re-injected into the field for storage and enhanced natural gas production. Injection is still ongoing and so far about 90kT of CO_2 have been injected. Different monitoring technologies have been deployed, with the overall aim of studying relevant processes for underground CO_2 storage in depleted gas fields, but with the primary aim of establishing wellbore integrity and assessing the potential for EGR.

Downhole and wellhead measurements of temperature, pressure and flow rate have been acquired for the gas production and CO_2 injection wells, and provide the input data for reservoir simulations. At the start of CO_2 injection in 2004 this data was updated on an hourly basis, but later the frequency was changed to daily updates.

Since the injected CO_2 originates from the same reservoir into which it is being re-injected, it cannot be chemically distinguished from naturally occurring CO_2 in the reservoir. Two perfluorocarbon chemical tracers were therefore injected to investigate the CO_2 migration patterns and EGR potential of the reservoir, as well as the partitioning behavior of the CO_2 and CH_4 (Figure 7-4).

Downhole sampling of water samples took place in 2010. Analysis of these samples gave an insight into the downhole conditions of the CO_2 injection well during shut-in. Downhole pressure and temperature gauges have been temporarily installed to perform pressure fall-off tests. These tests along with the results of reservoir modelling work have been used demonstrate that CO_2 injection at K12-B has performed successfully and has not lead to complications related to changes of reservoir permeability, increasing skin factors or wellbore storage. Samples from the gas production stream were taken at regular intervals and the composition of the produced gas was analyzed in order to support reservoir simulations and confirm interpretations of the reservoir dynamics.

All tests along with the results of reservoir modelling work have been used to demonstrate that CO_2 injection at K12-B is successful and has not lead to complications related to changes of reservoir permeability, increasing skin factors or wellbore storage.

Since the injected CO_2 originates from the same reservoir into which it is being re-injected, it cannot be chemically distinguished from naturally occurring CO_2 in the reservoir. Two perfluorocarbon chemical tracers were therefore injected to investigate the CO_2 migration patterns and EGR potential of the reservoir, as well as the partitioning behavior of the CO_2 and CH_4 (Figure 7-4).

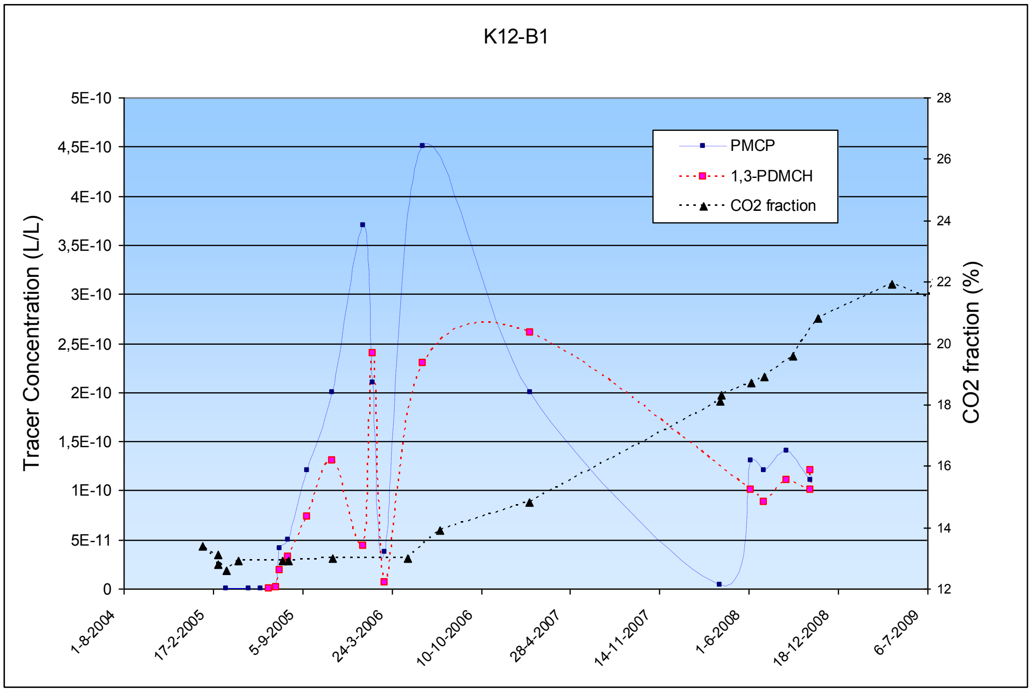

Figure 7-4 Tracer concentrations and CO2 fractions at the K12-B1 production well. Tracer concentration data for both tracers show tracer breakthrough after 130 days (August 2005) for the K12-B1 well and after 463 days for the 12-B5 well (June 2006).

Additional tracer tests are being planned for 2015. The objectives of these tracer tests are (a) to identify and test new chemical tracers specifically for (Dutch) gas field conditions and (b) to provide insights into the flow of CO_2 in the reservoir. The results will be useful for the assessment of the potential for Enhanced Gas Recovery. The project has identified and characterized suitable chemical tracers that are expected to migrate more closely with CO_2 as compared with previously injected tracers. Future plans at this site include co-injection of the tracers with the CO_2 stream, with monitoring for breakthrough times and concentration. Composition data from the production stream in combination with well head data will then be used to constrain reservoir simulations, leading to an improved understanding of processes relevant to CO_2 storage and EGR.

7.1.7 New offshore CO_2 storage projects in the planning phase

The planned CCS project at Peterhead-Goldeneye, offshore Scotland, involves injection into a depleted gas field and has a monitoring program designed to meet European offshore requirements and covering both deep and shallow focused monitoring. The deep-focused component will include surveillance of the reservoir and overburden and utilizes a number of proven technologies, including time-lapse 3D seismic, down-hole pressure and temperature, geophysical logging and fluid sampling. A comprehensive shallow environmental monitoring program is also planned, including seabed imaging, seabed sampling and seawater sampling technologies. Contingency monitoring is also addressed, for example a P-Cable seismic survey is planned to help image and understand shallow migration in the event of leakage being detected at the top of the storage complex.

The Dutch ROAD project is the first project to be permitted under the EU Storage Directive. The permit is subject to updates and the inclusion of more detail. Around 1.1 Mtpa of CO_2 is planned to be transported to a depleted gas field 20 km (12 miles) off the coast of Rotterdam. The target reservoir will be the P18-4 gas reservoir (operated by TAQA). Further work is underway to assess specific local pressure build-ups, pressure barriers and later-stage fault leakage. Results will be used to update the risk assessment which will feed into the updated monitoring plan to provide evidence for containment and to demonstrate integrity of seals, faults and wells.

The Japanese Tomakomai CCS project is a large scale demonstration project located 3-4 km off the coast of Hokkaido. The monitoring program includes 2D and 3D seismic surveys. These will be deployed via OBCs because greater repeatability is achievable and the busy port and shallow water setting precluded streamer deployment. The 2D survey line aligns with the two injection wells and uses a buried OBC for similar reasons. Heavy emphasis has been placed on the detection of natural earthquakes and microseismicity which also uses the OBC equipment, in addition to four dedicated ocean bottom seismometers (OBS) and downhole sensors in the observation wells. Various kinds of marine environmental monitoring are also scheduled, as required by Japanese regulation.

7.2 Offshore monitoring technology

7.2.1 Time-lapse seismic methods

Time-lapse seismic is a mature technology used to monitor gas and oil production worldwide, and it has also been successfully employed for monitoring many saline aquifer CO_2 injection sites, both onshore and offshore. The technology is based on the acoustic contrast between the low velocity and density of CO_2 compared to the higher velocity and density of the *in situ* brine. Both repeated 2D and 3D seismic have been employed for CO_2 monitoring and the results typically give a detailed image of the lateral and vertical distribution of CO_2 in the pore space. The method is best employed at sites where the injected CO_2 properties give a good contrast with the in situ pore fluid—generally good within saline aquifers but less favorable for CO_2 injection into produced gas fields. Although the level of detail possible with seismic imaging is relatively high, it is restricted by the seismic wave length and there is a lower resolution limit beneath which time-lapse changes will not be resolved (typically around 10-15m). The method depends on a precise repetition of the seismic surveys, and it is particularly important to reproduce the position of the seismic source and receivers. Marine 3D seismic acquisition and time-lapse seismic monitoring is constantly improving, e.g., using guided and steerable streamer technology. These improvements lead to a paradox in any time-lapse monitoring project. Although there is a desire to always use the most updated technology, the base line survey is often the limiting factor when taking advantage of the newer technology available for repeat surveys. In recent years there has been a development towards broadband seismic technologies, aimed at expanding the frequency range for seismic acquisition. Time-lapse processing is used to make these newer surveys backward compatible with the (typically poorer) base line survey.

Time-lapse seismic has been the main monitoring technology employed from the start at the Sleipner injection site, and has provided a detailed overview of the CO_2 behavior in the reservoir.[239,240] (Figure 7-5) shows the typical time-lapse response at Sleipner, between the 1994 (base survey) and the repeat 2010 survey. In total, nine different layers were identified at Sleipner from the 4D seismic monitoring. These imaged layers are interpreted as being due to CO_2 partially trapped beneath thin mudstone layers within the Utsira sandstone storage unit (due to capillary forces), and then migrating upwards towards the top of the storage unit. These thin shales were identified in wells at the outset of the project[241] but their effect was unknown as the shales could not be correlated from well logs alone or seen on the baseline seismic data. Time-lapse seismic imaging has therefore revealed which geological units actually control the dynamics of CO_2 plume movement, leading in turn to an improved appreciation of the physics and dynamics of CO_2-brine multiphase flow systems.[242,243,244]

[239] Arts, R.J., Chadwick, A., Eiken, O., Thibeau, S., Nooner, S., [2008] Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway. First Break 26(1), 65-72.

[240] Furre, A. K., and Eiken, O. (2014). Dual sensor streamer technology used in Sleipner CO_2 injection monitoring. *Geophysical Prospecting,* 62(5), 1075-1088.

[241] Zweigel P, Arts R, Lothe AE and Lindeberg EBG, 2004. Reservoir geology of the Utsira Formation at the first industrial-scale underground CO_2 storage site (Sleipner area, North Sea). In: Baines SJ editor. Geological Storage of Carbon Dioxide. Geological Society special publication no. 233, p. 165-180.

[242] Singh, V., Cavanagh, A., Hansen, H., Nazarian, B., Iding, M. and Ringrose, P., 2010. Reservoir modeling of CO_2 plume behaviour calibrated against monitoring data from Sleipner, Norway. SPE 134891, presented at the SPE Annual Technical Conference and Exhibition held in Florence, Italy, 19–22 September 2010.

[243] Chadwick, R. A., and Noy, D. J., 2010. History-matching flow simulations and time-lapse seismic data from the Sleipner CO_2 plume. In Geological Society, London, Petroleum Geology Conference series (Vol. 7, pp. 1171-1182). Geological Society of London.

[244] Cavanagh, A., 2013. Benchmark Calibration and Prediction of the Sleipner CO_2 Plume from 2006 to 2012. Energy Procedia, 37, 3529-3545.

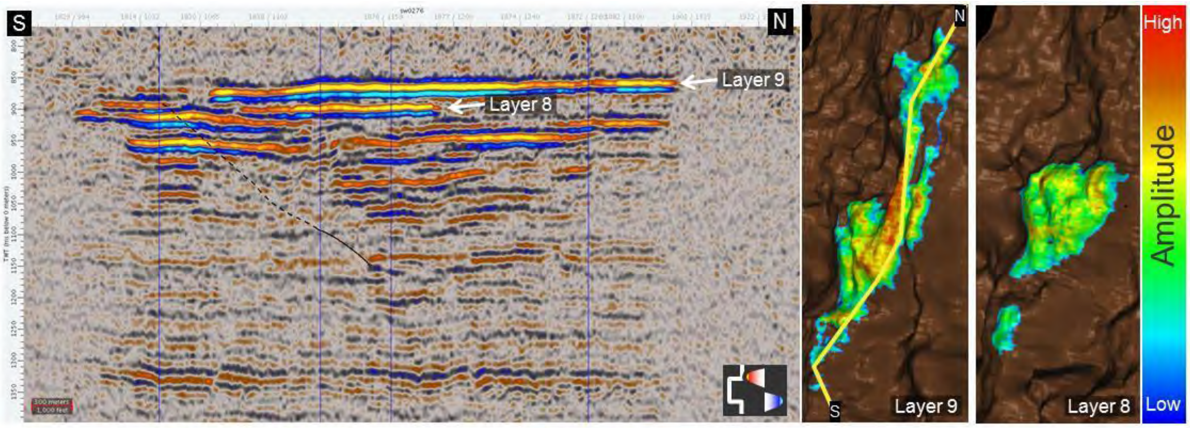

Figure 7-5 Time-lapse response (1994 to 2010). Left: seismic difference section, right: map view of the two uppermost layers.

The time-lapse seismic response is potentially influenced by changes in saturation, pressure or rock strain, or more generally a combination of all these factors. While at Sleipner the response is mainly related to saturation (since pressure changes are very small), at the Snøhvit site it seems that the observed response is related to both pressure and saturation changes.[245] Although this can complicate the interpretation of time-lapse seismic, it also brings the potential for resolving both the pressure footprint and the spread of the CO_2 plume itself from seismic monitoring datasets.

7.2.2 Other geophysical methods

The most successful alternative geophysical monitoring technique has probably been time-lapse gravity, which has been employed both at the Sleipner and Snøhvit injection sites.[246,247,248] Time-lapse gravity monitoring is based on accurately measuring the difference in the Earth's mass attraction when the *in situ* brine is replaced by lower density CO_2. The methodology was developed for offshore monitoring by Statoil in co-operation with the Scripps Research Institute during the late nineties and was first successfully used in monitoring gas production from the Troll field. The success of the method depends on the instrument precision and position accuracy. Typically concrete benchmarks are placed on the seafloor in a grid covering the injection site and the gravimeter is deployed using an ROV and then retrieved from the benchmark after sufficient time to correct for tidal effects and long-term drift. This allows a precision in the range of 2-5

[245] Grude, S., Landrø, M., and Osdal, B. (2013). Time-lapse pressure–saturation discrimination for CO_2 storage at the Snøhvit field. *International Journal of Greenhouse Gas Control,* 19, 369-378.

[246] Nooner, S. L., Eiken, O., Hermanrud, C., Sasagawa, G. S., Stenvold, T. and Zumberge, M. A., 2007. Constraints on the in situ density of CO_2 within the Utsira formation from time-lapse seafloor gravity measurements. *International Journal of Greenhouse Gas Control,* 1, 198 – 214.

[247] Alnes, H, Eiken, O., Stenvold, T., 2008, Monitoring gas production and CO_2 injection at the Sleipner field using time-lapse gravimetry Geophysics, Vol 73, no 6 (November-December 2008), P. WA 1555-WA 161.

[248] Alnes, H, Eiken, O., Nooner, S., Sasagawa, G., 2011. Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO_2 plume. *Energy Procedia,* 4, 5505-5511.

microgalileos (μGals), (which is a unit of acceleration defined as one-millionth of a Gal, which is 1 cm/s^2) comparable to the best onshore gravimetric surveys.

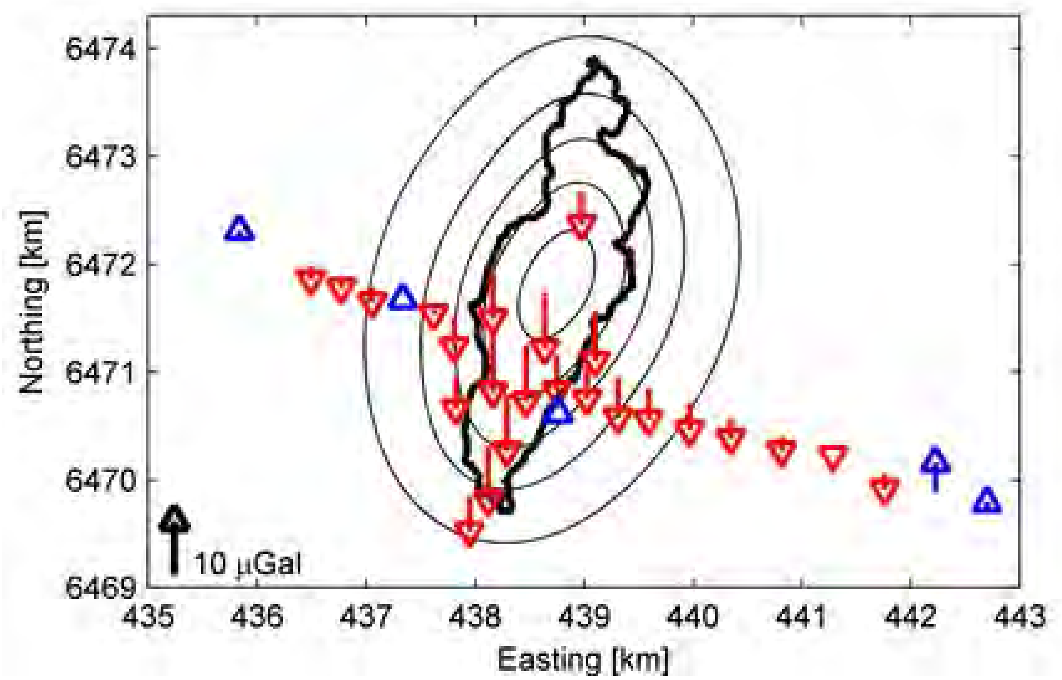

Figure 7-6 Map of observed gravity changes at Sleipner between 2002 and 2009 (corrected for measured benchmark settling, and after water influx signal has been subtracted), redrawn from Alnes et al 2011. Red arrows denote a reduction in seafloor gravity (scale i s shown in the bottom left hand corner). Contours show modelled gravity response from the CO_2 plume (contour spacing is 2 μGal). Thick black outline shows the outline of the CO_2 plume estimated from the seismic response in 2008.

Figure 7-6 shows the gravimetric layout over the Sleipner field, together with the gravimetric time-lapse response from 2002 to 2009. The advantage of the gravimetric method is that it provides a direct estimate of the CO_2 density change in the reservoir (as opposed to seismic which is a mixed response of density and velocity); however, the disadvantage is that gravimetric measurements have much less resolution than seismic measurements. In practice, gravity surveys are most useful when used in combination with time-lapse seismic, allowing density changes to be more precisely calibrated.

Repeated resistivity measurements downhole have been used successfully for monitoring resistivity changes at the onshore Ketzin CO_2 injection test site.[249] In the offshore setting, where downhole monitoring in wells is much more limited, an attractive alternative is to use CSEM waves with sources and receivers towed close to the seabed. CSEM has had a rapid development as a

[249] Bergmann, P., Schmidt-Hattenberger, C., Kiessling, D., Rücker, C., Labitzke, T., Henninges, J., and Schütt, H. 2012. Surface-downhole electrical resistivity tomography applied to monitoring of CO_2 storage at Ketzin, Germany. Geophysics, 77(6), B253-B267.

supplement to seismic for oil exploration purposes and relies on measuring the resistivity difference between a more resistive oil or gas bearing rock formation compared to the formation filled with saline brine. CSEM surveys also provide relatively low resolution measurements. A feasibility test was conducted at the Sleipner CO_2 storage site in 2006, but did not give conclusive results, however the method shows some potential especially when combined with gravity field monitoring.[250]

7.2.3 Downhole monitoring

Onshore CO_2 storage sites, such as the demonstration projects at Ketzin,[251] Decatur,[252] Bell Creek,[253] and Cranfield[254] have tended to have a stronger focus on downhole monitoring, including use of downhole gauges, distributed fiber-optic measurements, repeat saturation logging, downhole electrical resistivity tomography, and downhole seismic measurements. In the offshore setting, where well construction and operations costs are significantly higher, downhole monitoring for CO_2 storage has so far been more limited. However, following significant technical advances in down-hole fiber-optic deployed measurement devices,[255] downhole monitoring in the offshore setting has become a more practical and cost-effective option.

Permanent downhole monitoring approaches recently applied in the oilfield setting include:

- Permanent quartz gauges with a range of acoustic, copper or fiber-optic transmission systems;
- Distributed temperature sensing (DTS) systems where the fiber optic cables are used to measure temperature changes along the fiber;
- Distributed acoustic sensing (DAS), where the fiber optic cables are used to measure strain.

These permanent downhole sensors are most commonly deployed attached to the injection (or production) tubing with transmission to surface via single-mode fiber or multiple fibers in a single tube. Fiber optic cables and downhole gauges may also be placed behind the well casing or in dedicated monitoring wells. At the Citronelle (United States) test site, a DAS cable was deployed

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[250] Park, J., Vanneste, M., Waarum, I. K., Sparrevik, P. M. and Sauvin, G., 2014. In Situ Resistivity of CO_2 Plume at Sleipner from CSEM and Gravity Data. Extended abstract presented at the First Applied Shallow Marine Geophysics Conference, 14-18 September 2014 (EAGE).

[251] Bergmann, P., Schmidt-Hattenberger, C., Kiessling, D., Rücker, C., Labitzke, T., Henninges, J., and Schütt, H. 2012. Surface-downhole electrical resistivity tomography applied to monitoring of CO_2 storage at Ketzin, Germany. Geophysics, 77(6), B253-B267.

[252] Finley, R. J., 2014. An overview of the Illinois Basin–Decatur project. Greenhouse Gases: Science and Technology, 4(5), 571-579.

[253] Gorecki, C. D., Hamling, J. A., Ensrud, J., Steadman, E. N., and Harju, J. A. (2012). Integrating CO_2 EOR and CO_2 Storage in the Bell Creek Oil Field. Carbon Management Technology Conference. doi:10.7122/151476-MS

[254] Meckel, T. A., and S. D. Hovorka, 2009. Results of continuous downhole monitoring (PDG) at a field-scale CO_2 demonstration project, Cranfield, MS. In SPE International Conference on CO_2 Capture, Storage, and Utilization. San Diego, California, pp. 4-9.

[255] Eck, J., Ewherido, U., Mohammed, J., Ogunlowo, R., Ford, J., Fry, L., and Veneruso, T., 1999. Downhole monitoring: the story so far. *Oilfield Review,* 11(3), 18-29.

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as part of a Modular Borehole Monitoring (MBM) system alongside electrical cables for geophone and P/T data, and a u-tube for fluid sampling.[256] Improvements in the reliability of the installation process and in the long-term stability of the gauges and fibers at high temperatures and pressures have taken the performance lifetime from a few months to several years, meaning that the systems can now be considered as permanent for the lifetime of most projects (10–30 years). The value of permanent downhole gauges for CO_2 storage monitoring has now been demonstrated at several sites, both onshore[257] and offshore (at the Snøhvit and K12-B sites). Distributed temperature and acoustic sensing has been field tested at several onshore CO_2 storage sites including Otway (Australia), Ketzin (Germany), Decatur and Citronelle (United States),[258] where the value of DAS for acquiring vertical seismic profile (VSP) datasets shows great potential as an advanced and cost effective approach for MMV. Field trials for acquiring VSP data from distributed acoustic sensing systems deployed in offshore gas production wells have also been recently demonstrated,[259] such that use of DAS and DTS systems is likely to be an important part of future offshore CO_2 storage projects.

Interpretation of downhole monitoring data will always require integration with other subsurface data, including geological data, surface seismic data, and fluid characterization and modelling. The value of this integrated approach to monitoring and verification of CO_2 storage sites is clear from many case studies, and nicely illustrated for the offshore setting by Snøhvit CO_2 injection project, where downhole pressure gauge data were interpreted alongside time-lapse surface seismic data to design a well intervention operation.[260,261] Figure 7-7 illustrates how the time-lapse seismic response at Snøhvit was subsequently confirmed by downhole flow logging data, confirming the value of combining a range of monitoring data (in this case surface seismic data with downhole pressure gauge and flow logging data) in order to optimize and manage CO_2 storage in an offshore setting.

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[256] Daley, T. M., Freifeld, B. M., Ajo-Franklin, J., Dou, S., Pevzner, R., Shulakova, V., and Lueth, S., 2013. Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring. *The Leading Edge,* 32(6), 699-706.

[257] Couëslan, M. L., Smith, V., El-Kaseeh, G., Gilbert, J., Preece, N., Zhang, L., and Gulati, J., 2014. Development and implementation of a seismic characterization and CO_2 monitoring program for the Illinois Basin–Decatur Project. *Greenhouse Gases: Science and Technology,* 4(5), 626-644.

[258] Daley, T. M., Freifeld, B. M., Ajo-Franklin, J., Dou, S., Pevzner, R., Shulakova, V., and Lueth, S., 2013. Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring. *The Leading Edge,* 32(6), 699-706.

[259] Nørgaard Madsen, K.,Thompson, M., Parker, T., Finfer, D., 2013, A VSP field trial using distributed acoustic sensing in a producing well in the North Sea, First Break 31 (11) pp. 51 – 56.

[260] Hansen, O., Gilding, D., Nazarian, B., Osdal, B., Ringrose, P., Kristoffersen, J-B., Eiken, O., Hansen, H., [2012] Snøhvit: The history of injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm. Energy Procedia, 37, 3565 – 357.

[261] Osdal, B., Zadeh, H. M., Johansen, S., Gonzalez, R. R., and Wærum, G. O., 2014. Snøhvit CO_2 Monitoring Using Well Pressure Measurement and 4D Seismic. Fourth EAGE CO_2 Geological Storage Workshop, April 2014.

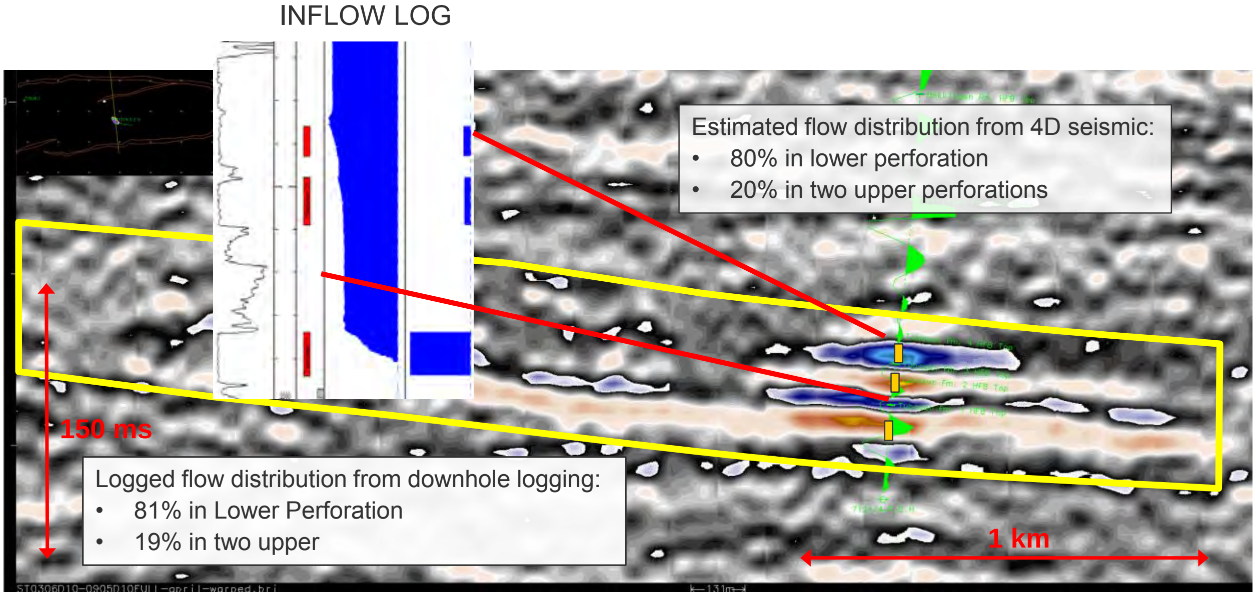

Figure 7-7 Comparison of downhole flow logging at the Snøhvit CO_2 storage site with flow distribution estimate from time-lapse (4D) seismic (yellow box indicates the Tubåen storage unit).

7.2.4 Shallow-seismic monitoring

Various technologies currently exist for investigating the shallow sub-seabed, the sediment-water interface and overlying water column. These include shallow seismic methods, acoustic methods (swath bathymetry, sonar), coring, underwater imagery, and chemical sampling. Near-seafloor monitoring techniques are undergoing rapid development and are now being applied to CO_2 storage issues; including establishing baseline datasets, understanding spatial and temporal sampling requirements, and improving detection thresholds. Figure 7-8 illustrates the various methods available for addressing monitoring, risk assessment and site selection issues. Here we will first review shallow seismic monitoring methods and then passive seismic and seabed monitoring in the following sections.

There is a wide range of offshore seismic acquisition and monitoring technologies available for subsurface geologic characterization, which need only minor modification adaptation for CCS. In heavily explored hydrocarbon basins, baseline 3D seismic surveys are widely available, and for other offshore basins new 2D and 3D seismic data can be easily acquired. Newer high resolution 3D (HR3D) seismic technologies [262], [263] (e.g., the P-cable) are especially valuable for characterization of the overburden stratigraphy Figure 7-9. Such acquisition systems have been deployed for the Snøhvit site in the Barents Sea Basin as well as for the potential CO_2 storage site

[262] Planke, S., F.N. Eriksen, C. Berndt, J. Mienert, and D.G. Masson, 2009, P-cable high-resolution 3D seismic, *Oceanography,* 22, 81.

[263] Steeghs, P., Vandeweijer, V.P., Mosher, C.C., Ji, L. and De Kleine, M.P.E., Acquisition and Processing of a High Resolution 3D Seismic Survey – Offshore Netherlands, 77th EAGE Conference and Exhibition, 2015

P18, offshore the Netherlands. When integrated with deeper regional conventional 3D seismic data and petroleum exploration data, HR3D becomes a valuable tool for characterizing regional seals and mapping faults that may extend vertically from hydrocarbon and CO_2 storage reservoir depths through confining systems.

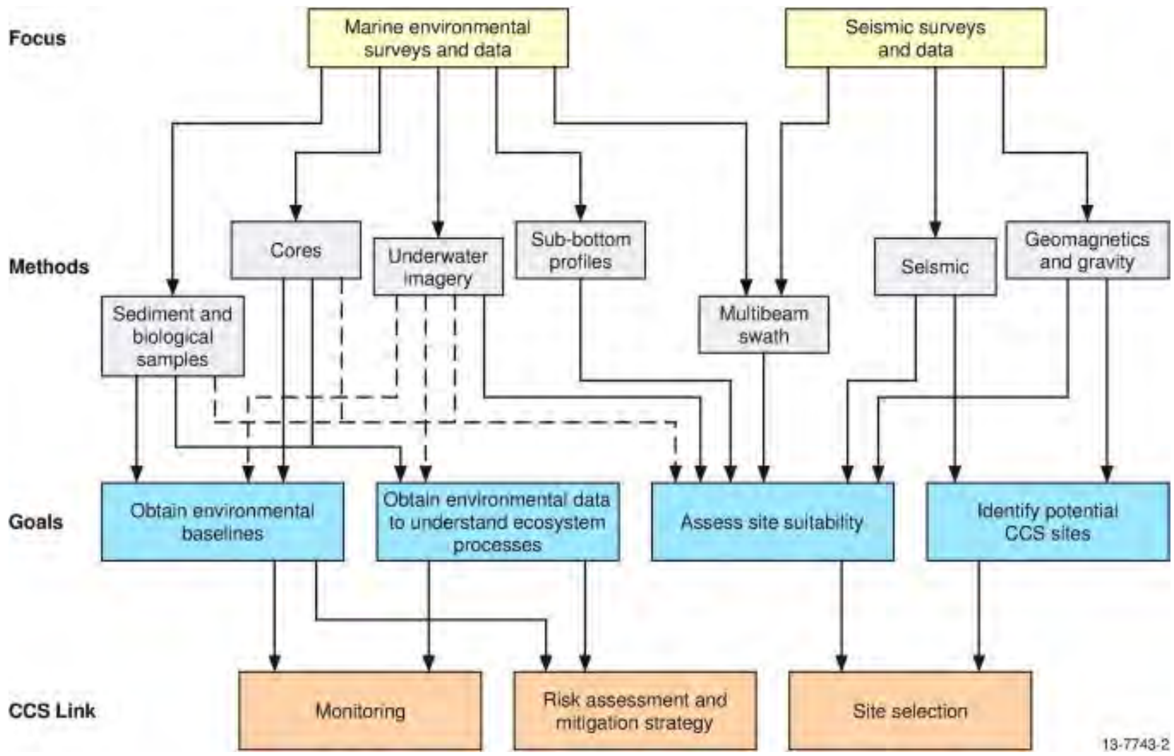

Figure 7-8 Diagram showing the roles of environmental (seabed and shallow sub-seabed) and deep geological (seismic) data to sub-seabed storage of CO_2. Solid lines indicate likely relationships, and dashed lines indicate potential relationships. [264]

From 2012 to 2014, three HR3D surveys have been conducted on the inner shelf (<10 miles) offshore Texas in the Gulf of Mexico as part of a project to characterize CO_2 storage potential. During 2014 another type of HR3D survey was executed just offshore the Netherlands in the vicinity of the P18 gas field, a potential CO_2 storage location for the ROAD project. These surveys have identified gas migration pathways and shallow re-accumulations, providing insight into CO_2 storage and long-term fate of buoyant mobile phases. HR3D data can identify stratigraphy and faults in the overburden in unprecedented resolution (well below conventional seismic resolution (Figure 7-9), and provide crucial information for proving up storage prospects (seal continuity and potential migration pathways). Observations from these surveys indicate the value of HR3D data for discriminating between favorable and unfavorable storage settings with

[264] Carroll, A.G., P. Przeslawski, L.C. Radke, J.R. Black, K. Picard, J.W. Moreau, R.R. Haese, and S. Nichol, 2014, Environmental considerations for sub-seabed geological storage of CO_2: A review, Continental Shelf Research, 83: 116-128.

respect to long-term containment, as well as potential for time-lapse monitoring for leakage from engineered injections.

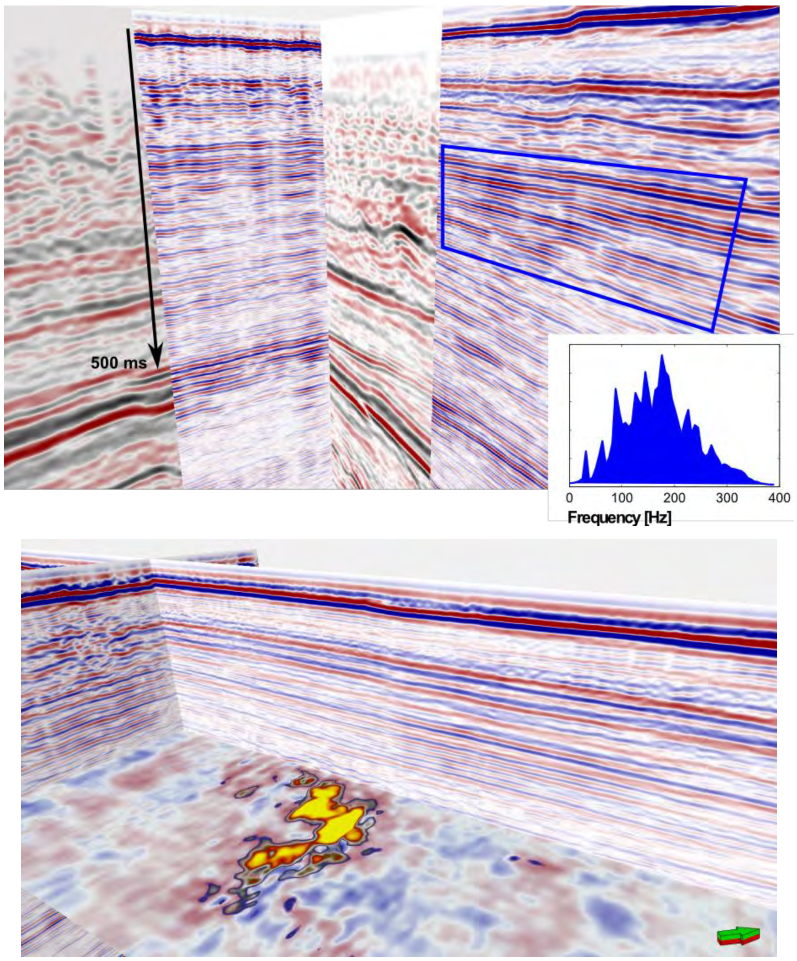

Figure 7-9 (Top) Comparison of data from a conventional seismic survey with HR3D data. Conventional data has poor shallow coverage and resolution. (Below) shallow gas pocket delineated in HR3D survey near the ROAD project's candidate storage location.

7.2.5 Passive and induced seismic monitoring

One particular concern for CO_2 storage security is the potential risk of induced seismicity.[265,266] A major technical challenge is that induced seismicity needs to be differentiated from a background of natural seismicity. In general, land-based seismic monitoring networks are much better

[265] Zoback, M.D., Gorelick, S.M., 2012. Earthquake triggering and large-scale geologicstorage of carbon dioxide. PNAS 109, E3624–E3624.

[266] Verdon, J.P., 2014. Significance for secure CO_2 storage of earthquakes induced by fluid injection. Env. Rev. Lett 9, 064022.

developed than offshore networks, such that the starting point for understanding background seismicity is generally poor.

Seismic events offshore can be monitored by seismographs such as OBS. Offshore reservoir monitoring tools such as OBCs and ocean bottom nodes (OBN) can also be used for event hypocenter determination of microseismic events around a reservoir zone or storage unit. The combination of OBS and OBC/OBN monitoring should be useful for distinguishing induced seismic events from natural events, but is currently an emerging technology and will be demonstrated in the Japanese Tomakomai Project (Figure 7-10), where CO_2 injection is planned for 3 years, starting in 2016. Some onshore CO_2 storage sites, including Weyburn,[267] In Salah[268,269] and Decatur[270] have successfully tested microseismic monitoring for CO_2 storage revealing the potential for using the approach to monitor microseismicity associated with CO_2 injection. A key issue emerging from these studies is that detected events are generally controlled by pressure and stress changes and only indirectly associated with CO_2 injection. Development of high quality velocity and geomechanical models is therefore essential for successful application of this technology.

[267] Verdon, J. P., Kendall, J. M., White, D. J., and Angus, D. A. (2011). Linking microseismic event observations with geomechanical models to minimise the risks of storing CO_2 in geological formations. Earth and Planetary Science Letters, 305(1), 143-152.

[268] Oye, V., Aker, E., Daley, T. M., Kühn, D., Bohloli, B., and Korneev, V. (2013). Microseismic monitoring and interpretation of injection data from the In Salah CO_2 storage site (Krechba), Algeria. Energy Procedia, 37, 4191-4198.

[269] Stork, A.L., Verdon, P.J., Kendall, J.-M., 2015. The microseismic response at the In Salah Carbon Capture and Storage (CCS) site. Int. J. Greehouse Gas Control 32, 159–171.

[270] Couëslan, M. L., Smith, V., El-Kaseeh, G., Gilbert, J., Preece, N., Zhang, L., and Gulati, J., 2014. Development and implementation of a seismic characterization and CO_2 monitoring program for the Illinois Basin–Decatur Project. Greenhouse Gases: Science and Technology, 4(5), 626-644.

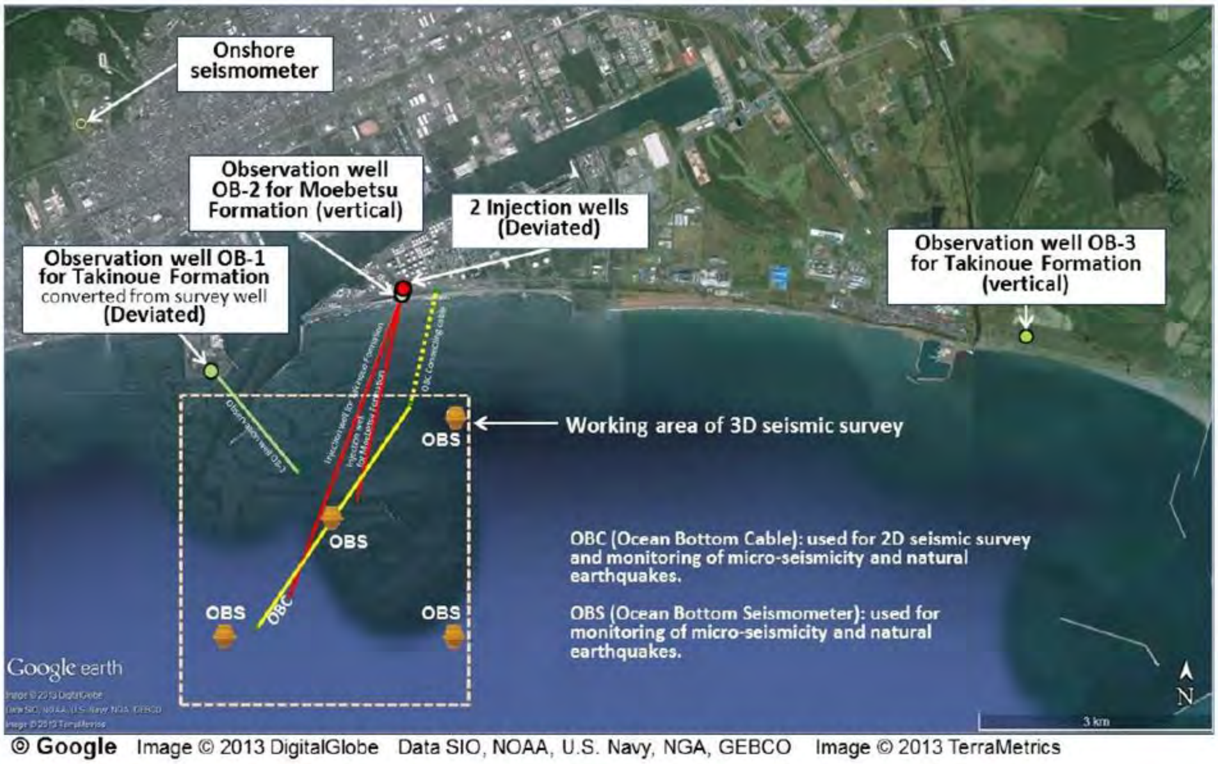

Figure 7-10 Layout of the monitoring facilities at the Tomakomai CCS Demonstration Project.

7.2.6 Marine and seabed monitoring

A number of studies have looked at natural leakage of CO_2 from the seabed[271] as an analogue for understanding possible leakage of CO_2 into the marine environment, while others have conducted controlled release experiments in the shallow marine environment.[272,273] In both cases the objective has been to understand how CO_2 leakage to the seabed might be detected and what the potential impacts could be to the marine environment.

An important research site is the QICS artificial CO_2 test injection experiment in Ardmucknish Bay off the west coast of Scotland. CO_2 was released beneath 11m of sediment over a period of 37 days. Although bubbles occurred soon after injection, CO_2 was retained within sediments and trapped in pore waters. The QICS experiment also clearly revealed the influence of cyclical hydrostatic pressure induced by tides. By using dispersed transponders it is possible to detect the location of bubble streams by triangulation. Although the system allows continuous measurement

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[271] Pearce, J. M. (2006). What can we learn from natural analogues?; Advances in the geological storage of carbon dioxide (pp. 127-139). Springer Netherlands.

[272] Tait, K., Stahl, H., Taylor, P., and Widdicombe, S., 2014. Rapid response of the active microbial community to CO_2 exposure from a controlled sub-seabed CO_2 leak in Ardmucknish Bay (Oban, Scotland). International Journal of Greenhouse Gas Control, doi:10.1016/j.ijggc.2014.11.021

[273] Kita, J., Stahl, H., Hayashi, M., Green, T., Watanabe, Y., and Widdicombe, S., 2014. Benthic megafauna and CO_2 bubble dynamics observed by underwater photography during a controlled sub-seabed release of CO_2. International Journal of Greenhouse Gas Control. doi:10.1016/j.ijggc.2014.11.012

it is susceptible to biofouling, suspended sediment and trawler damage. One of the main challenges encountered with passive acoustic measurements is the extent of background noise from artificial and natural sources which can mask a specific acoustic signal.

The controlled release experiments conducted by the QICS research project demonstrate that leaks of CO_2 gas can be detected by monitoring acoustic, geochemical and biological parameters within a given marine system. However the natural complexity and variability of marine system responses to (artificial) leakage strongly suggests that there are no absolute indicators of leakage or impacts that can unequivocally and universally be used for all potential future storage sites. These studies suggest that a multivariate, hierarchical approach to monitoring is needed, escalating from anomaly detection to attribution, quantification and then impact assessment, as required. Proposed optimal spatial and temporal criteria for baseline surveys relating to each category of monitoring approach are detailed in Table 7-3. The particular choice of approaches will have some site specificity. QICS suggested that acoustic and geochemical methods will be the primary detection methodologies and therefore identify the most pressing aspects of baseline generation. Given the spatial heterogeneity of many marine ecosystems it is essential that environmental monitoring programs are supported by a temporally (tidal, seasonal and annual) and spatially resolved baseline of data from which changes can be accurately identified.

Table 7-3: Optimal spatial and temporal criteria for baseline surveys relating to each category of monitoring approaches suggested from QICS controlled release experiment

Methodology	Variables	Temporal sampling interval	Spatial sampling scale	Notes
Active acoustics	Seafloor bathymetry, including pockmarks.	In shallow waters where the seafloor sediments are exposed to storm-driven resuspension and biological sedimentation a seasonal discrimination, in the first instance. In deeper waters where sediments are disconnected from weather driven events an initial survey, followed by a repeat survey 1–2 years later.	The spatial extent of the storage reservoir in addition to allowing for lateral movement of migrating CO_2.	Assists identification of existent natural seeps.
	Free gas in surface sediments and water column.	An initial survey, followed by a repeat survey 1–2 years later.		Useful for attribution.
Passive acoustics	All noise at relevant frequencies.	Seasonal in addition to targeted short-term deployments to assess event driven noise.	Targeted to known fixed installations or shipping routes.	Necessary for quantification, not essential for detection.
	Acoustics of existent natural gas seeps.	Seasonal and targeted short term deployments to account for intermittent gas flow.	Spatial extent of the storage reservoir as well as allowing for lateral	Required for detection.

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Methodology	Variables	Temporal sampling interval	Spatial sampling scale	Notes
			movement of migrating CO_2.	
Geochemistry	Water column pH, pCO_2, temperature, salinity, pressure. TA or DIC and O_2 if possible.	Hourly measurements for at least part of the seasonal cycle, corresponding with periods of biological or physical activity. Weekly for entire annual cycle. Repeated for at least one subsequent year to assess inter-annual variability and then on an approximately decadal repeat to assess longer term trends.	For high frequency data, if the storage site is large or includes significant changes in water depth or other hydrodynamic properties, at least a pair of landers deployed across the site. Spatial extent of the storage site via AUV deployment.	Required for detection.
	Isotope composition ratios: e.g., C^{13}:C^{12}	Occasional (not dynamic)	Occasional (not dynamic)	Addresses attribution
Biology	Community structure, indicator species and related indices.	Weekly during periods of intense biological activity, otherwise monthly. Repeated for at least one subsequent year to assess inter-annual variability and then on an approximately decadal repeat to assess longer term trends.	Significant differences in water depth and-or different sediment types within the complex would need separate characterization. Multiple replicates are required for statistical certainty.	Principally for impact assessment.

Natural CO_2 seepage sites are prevalent in several areas around the world and especially in geothermally active areas. The hydrothermally driven seeps off the island of Panarea in the Aeolian Islands are a good example. Observations near these seeps show that the local biology has adapted to the presence of these seeps, but this adaptation is in distinct contrast to conditions in colder, deeper and more turbid sites. The Hugin Fracture is another example of a natural seepage, in this case in the central North Sea. Here, a 3 km long seabed structure is covered by soft sediments with wide patches of methanotrophic bacteria which metabolize methane from a natural seep. There is no evidence of CO_2 at this location.

The use of high-resolution seismic reflection using chirp and boomer technology is a valuable technology for near-surface monitoring, and proved highly effective during the QICS experiment. The technique produced clear images of gaseous CO_2 trapped in sediments above the release point (Figure 7-11).

The experience being gained from experimental and natural seepage sites highlights some key issues that affect offshore monitoring programs. Monitoring strategies need to be devised to cover large areas, typically tens to hundreds of km^2 and yet also achieve accurate measurement and

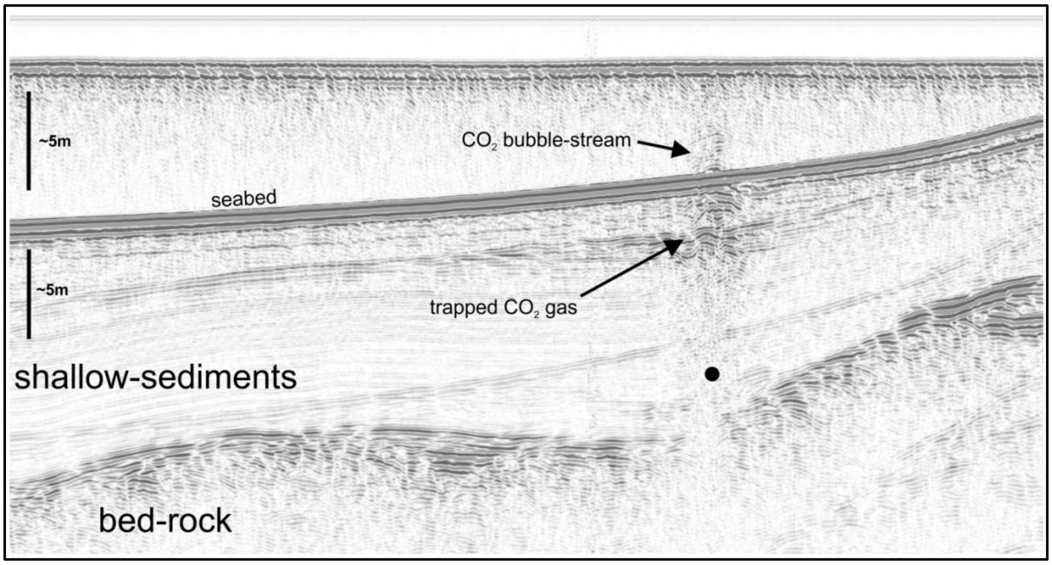

Figure 7-11 Seismic profile at the QICS site showing gaseous CO_2 trapped in shallow sediments and a bubble stream above the release point.

characterization over sufficiently long periods in order to understand temporal fluctuations. Limited spatial coverage could increase the risk that anomalies remain undetected. Monitoring data should be used to build a robust baseline but data interpretation can be used to improve the knowledge of storage sites and where anomalies could occur. A combination of point sampling and large spatial surveys should help to improve the quality of monitoring. Search areas could be narrowed down by the integration of information from deeper-focused monitoring such as 3D seismic, which can identify migration pathways, with shallow surface monitoring such as acoustic detection.

Seasonal variability, seawater chemistry variability and other features such as the presence of shallow gas (CH_4, CO_2, H_2S) in marine sediments need to be considered in any monitoring program. Other factors such as seabed recycling and sediment transport and anthropogenic activities such as trawling also need to be taken into account.

7.3 Technical challenges and technology gaps

7.3.1 Importance of data integration

Based on the recent record of monitoring technology development, we can expect further steady progress with novel monitoring approaches, improved detection and resolution, and more cost-effective survey methods. Despite these improvements, it is important to emphasize that measurement of CO_2 in the subsurface will always carry inherent uncertainties. Detection of changes in fluid saturation or pressure must always be compared to a background signal. This is clearly the case with time-lapse seismic monitoring of CO_2 plumes, where the “fluid signal” needs to be differentiated from the “rock signal”, but it is also the case apparently more direct downhole measurements. The successful track record of CO_2 storage monitoring at Sleipner and Snøhvit, clearly illustrates the importance of using multiple datasets (e.g., seismic, gravity and well data) in order to understand the nature of the monitoring data being interpreted.

Furthermore, it is increasing clear that CO_2 storage modeling and monitoring activities have to function in an iterative loop, with improved monitor data used to refine models[274] and improved model understanding used to improve the accuracy of monitoring data.[275,276] Using this experience from the early offshore CCS demonstration projects, we can develop realistic expectations on what can be detected from monitoring data, and use this insights to guide the implementation of the appropriate monitoring regulations.

7.3.2 Challenges for monitoring

This need for data integration and realistic expectations from monitoring data gives a good framework for understanding the main challenges for MMV, which can be summarized as follows:

1. Understanding the requirements for baseline datasets versus monitoring surveys: Technology evolves with time, and baseline datasets will typically have less advanced content than the latest survey data.
2. Marine and seabed surveys need to assess the range of natural variation, spatially and temporally, in order to establish a reference for detection of possible anomalies.
3. CO_2 storage monitoring requires some knowledge of the whole storage complex, including the overburden sequence and a fairly large volume around the storage site, leading to the question of how much data is really needed and over what volume?
4. Rock strain and the geomechanical response to CO_2 injection is relatively poorly understood and so the basis for differentiating natural (passive) seismicity from induced seismicity is challenging.
5. The interests of different stakeholders (e.g., the public, the regulator, the site operator) leads to challenging demands on the monitoring datasets, which will always have some inherent uncertainties.

7.3.3 Emerging technology

Many new and improved monitoring technologies have emerged in the last decade, and these are being tested and applied at the several industrial and pilot-scale CO_2 storage projects currently in operation. We can expect this trend to continue. It is useful to highlight some of these

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[274] Cavanagh, A. 2013. Benchmark calibration and prediction of the Sleipner CO_2 plume from 2006 to 2012. *Energy Procedia,* 37, 3529-3545.

[275] Furre, A. K., and Eiken, O. 2014. Dual sensor streamer technology used in Sleipner CO_2 injection monitoring. *Geophysical Prospecting*, 62(5), 1075-1088.

[276] Furre, A. K., Kiær, A., and Eiken, O. 2015. CO_2-induced seismic time shifts at Sleipner. *Interpretation*, 3(3), SS23-SS35.

developments as a pointer to what technology might emerge in the near future. These technologies include:

1. Improved time-lapse seismic imaging using steerable streamer technology and broadband seismic technology;
2. Improvements in the accuracy of time-lapse gravimetric monitoring to resolve density changes;
3. Use of high-resolution 3D seismic technologies (e.g., P-cable) to obtain improved imaging of overburden sequences;
4. Use of high-resolution seismic reflection chirp and boomer technology for near-surface marine monitoring;
5. Use of OBS and OBC and OBN to monitor natural and induced seismic events;
6. Use of fiber optic cables for downhole monitoring, including systems with permanent quartz gauges, DTS systems and DAS systems.
7. Interpretation of tracers co-injected the with the CO_2 stream to monitor breakthrough times and concentrations;
8. A range of improved acoustic techniques (e.g., multibeam echosounders) for monitoring the seabed, including detection of gas fluxes.

7.4 Summary and Recommendations

1. Monitoring technology for offshore CO_2 storage can be considered as mature, with many emerging technologies potentially bringing higher quality surveillance at an acceptable cost level.
2. The long history of monitoring at the Sleipner and Snøhvit sites in Norway and the pilot-scale K12-B site in the Netherlands, can be used to demonstrate the value of several key technologies, including 4D seismic, gravity-field monitoring, downhole gauges, and the use of tracers, alongside routine wellhead monitoring.
3. The portfolio of monitoring techniques available for CO_2 geological storage offshore can be classed in terms of deep-focused (providing surveillance of the reservoir and deeper overburden) and shallow-focused (providing surveillance of the near seabed, seabed and water-column).
4. Deep-focused operational monitoring systems are dominated by the use of 3D seismic surveys which have been highly effective for tracking CO_2 plume development in Sleipner and Snøhvit reservoirs. Measurement of downhole pressure is also highly valuable, and the availability of reliable down-hole gauges and fiber-optic systems indicates that this will be important technology for the future.
5. Shallow-focused monitoring systems are less mature but are currently being developed and demonstrated. New marine sensor and existing underwater platform technology such as

AUVs and mini-ROVs enable deployment and observation over large areas at potentially relatively low cost. Seafloor and ocean monitoring technologies can detect dissolved phase CO_2, precursor fluids (using chemical analysis) and gas phase CO_2.

6. Developments in geophysical techniques (such as the P-Cable seismic system for higher resolution 3D data collection in the overburden) have shown that successful and effective integration of these shallow subsurface technologies with the seabed monitoring data can help to understand shallow migration processes.
7. Assessment of the results from both the operational (predominantly deep-focused) and research (predominantly shallow-focused) monitoring activities from Sleipner and Snøhvit indicates that many elements of the European storage requirements have been met at these large-scale sites which were both initiated before the CCS Directive was introduced.
8. There are currently several emerging offshore CO_2 storage projects, such as the Tomakomai in Japan, ROAD in the Netherlands and Peterhead-Goldeneye offshore Scotland, which are designing and adopting state-of-the art monitoring strategies for offshore storage.

It is important to maintain the momentum in technology development for monitoring of offshore CO_2 storage, especially via data and experience exchange, along with focused international knowledge-sharing workshops.

8 Summary of regulatory requirements for offshore storage

8.1 Introduction

There have been significant developments in the regulation of CO_2 geological storage offshore. This section will describe the main developments, starting with the international coverage of the London Convention, the regional coverage of OSPAR for the EU and North East Atlantic, the regulation implemented by Japan, and the regulatory situation in the United States. These have created an enabling regulatory situation for CCS offshore whilst ensuring the protection of the marine environment and other resources.

From 2004 to 2007, a considerable amount of both legal and technical work on the storage of CO_2 in sub-seabed geological formations was developed under the London Convention and its 1996 Protocol and the OSPAR Convention. The technical and legal work included consideration of the risks and benefits to the marine environment within the context of increasing atmospheric CO_2 absorption by the oceans. The conclusion of this work was that the Conventions should move to remove their prohibitions that applied to certain CO_2 geological storage project configurations, so as to facilitate and to regulate environmentally safe CO_2 geological storage. In timescales faster than most anticipated, the London Protocol was amended in November 2006 and OSPAR was amended in June 2007. The actual amendments include various provisions, conditions and restrictions so as to only allow environmentally sound CO_2 storage. In this process, three detailed guidelines were produced for risk assessment and management of CO_2 storage. Much of the material below is taken from Dixon (2009 and 2015).[277,278]

8.2 International Regulatory Requirements (Existing and Proposed)

8.2.1 London Protocol

The London Convention (1972)[279] and the London Protocol (1996)[280] are the global agreements regulating dumping of wastes at sea, with the intention of protection of the marine environment. The Convention consists of 87 countries, and the Protocol 45 countries (as of November 2014). The Protocol is an updated and more rigorous version of the Convention. The secretariat of the London Convention and the London Protocol is provided by the IMO. The London Protocol was ratified by sufficient countries so as to come into force in March 2006, and is intended to replace the Convention in time. The Protocol prohibits dumping of wastes or other matter except those specified in its Annex 1, and these require permitting and regulation. Examples of wastes or other

[277] Dixon T, Greaves A, Thomson J, Christophersen O, Vivian C. International Marine Regulation of CO_2 Geological Storage. Developments and Implications of London and OSPAR. GHGT-9. Energy Procedia 1 (2009) 4503-4510.

[278] Dixon T, Garrett J, Kleverlaan E.2015. Update on the London Protocol – Developments on Transboundary CCS and on Geoengineering. *Energy Procedia*, *Volume 63*, *2014*, *Pages 6623-6628 (Jan 2015)*

[279] London Convention 1972. Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter (London Convention 1972).

[280] Protocol to the London Convention 1996. Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter – protocol thereto.

matter which may be dumped include dredged material, fish waste and inert geological material. However, it appeared that the Protocol, because it included the sub-seabed in its scope, could prohibit CO_2 geological storage in several CCS project scenarios including CO_2 from an onshore source to an offshore platform for injection into a sub-seabed geological formation.

An amendment to the Protocol to the London Convention was proposed in April 2006 by Australia and supported by UK, Norway, France and Spain. This was voted on and agreed in November 2006 and came into force on 10 February 2007. All of this was in timescales far faster than most anticipated, due to the newly recognized impacts of atmospheric CO_2 upon the oceans with ocean acidification. The key elements of this amendment are as follows: added to the list of substances that can be dumped is:

"CO_2 streams from CO_2 capture processes for sequestration"

With the important caveats that*:*

"Carbon dioxide streams may only be considered for dumping, if:

1 disposal is into a sub-seabed geological formation; and

2 they consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture and sequestration processes used; and

3 no wastes or other matter are added for the purpose of disposing of those wastes or other matter." (IMO 2006a)[281]

This meant that the geological storage of CO_2 had its prohibition uncertainty removed, so long as it is geological storage, and the CO_2 can contain impurities but this cannot be used as route for dumping other wastes.

In addition, the Scientific Group for the Convention and the Protocol produced two sets of detailed guidelines on geological storage of CO_2 in the marine environment. For risk assessment and management of such activities, they produced the Risk Assessment and Management Framework for CO_2 Sequestration in Sub-seabed Geological Structure (known as the RAMF) (IMO 2006b),[282] which also helped them understand the processes and risks better themselves. They then produced Specific Guidelines for Assessment of CO_2 Streams for Disposal into Sub-seabed Geological Formation (known as the CO_2 Specific Guidelines or sometimes as the CO_2 Waste Assessment Guidelines—WAG) (IMO 2007).[283] Both these guidelines provide an environmental impact assessment process, with factors to be considered specifically for CO_2 storage activities. These

[281] IMO 2006a. International Maritime Organisation. Report of The 28th Consultative Meeting And The First Meeting Of Contracting Parties. LC 28/15. 6 December 2006. Annex 6.

[282] IMO 2006b. International Maritime Organisation. Report of The Meeting Of The SG Intersessional Technical Working Group On CO_2 Sequestration. LC/SG-CO2 1/7. 3 May 2006. Annex 3

[283] IMO 2007. International Maritime Organisation. Report of the 30th Meeting of the Scientific Group of the London Convention. LC/SG 30/14. 25 July 2007. Annex 3

guidelines drew upon the best available knowledge from scientific experts and guidance from IPCC sources, including the IPCC Special Report (IPCC 2005)[284] and the IPCC Guidelines for GHG Inventories (IPCC 2006).[285]

The basic structure of the RAMF guidelines is as follows, with a brief summary of the content:

1. ***Problem Formulation****—scope, scenarios, boundaries*

2. ***Site characterization****—capacity, integrity, leakage pathways, monitoring options, surrounding area, modelling of CO_2 behavior*

3. ***Exposure assessment****—properties of CO_2 stream, exposure processes and pathways, likelihood, scale*

4. ***Effects assessment****—consequences - sensitivity of species, communities, habitats, other users*

5. ***Risk characterization****—integrates exposure and effects - environmental impact, likelihood*

6. ***Risk management****—leak prevention, monitoring of CO_2 streams within and above formations—linked to performance monitoring and migration detection, and monitoring seafloor, water and biological if leakage is suspected - mitigation*

Regarding monitoring, the RAMF guidelines draw upon the information contained in the IPCC guidelines (2006).[286] It places monitoring techniques into two categories - those for measuring performance within the geology, and those for monitoring when leakage is suspected. The latter are more detailed and also can measure impacts, and include monitoring of sea water chemistry and ecological effects. Emphasis is made that the monitoring activities have to be revised in the light of monitoring results, and following the IPCC GHG guidelines (IPCC 2006),[286] the frequency of monitoring can be reduced as confidence grows in the security of storage. Also following the IPCC guidelines, the RAMF recognizes that each storage site will be different and so site characterization and risk assessments should be on a site-by-site basis. Overall, the primary focus of the RAMF is on geological storage in depleted hydrocarbon reservoirs and saline aquifers. They explicitly do not cover coal beds, basalts and salt caverns. Also they recognize that storage in geological formations under deeper waters, e.g., 500m, would require revised guidelines.

The CO_2 Specific Guidelines (IMO 2007)[284] are the transposition and refinement of the RAMF into the standard structure of London Convention waste assessment guidelines to assist regulators in their permit decisions. These require an 'impact hypothesis' to be produced as a statement of the expected consequences of disposal. The basic structure of the Specific Guidelines is as follows, with a summary of the content:

1. ***Introduction—****purpose and scope*

[284] IPCC 2005. Carbon Dioxide Capture and Storage. Cambridge University Press

[285] IPCC 2006. Guidelines for National Greenhouse Gas Inventories. Vol 2 Energy, Chapter 5, Carbon Dioxide Transport, Injection and Geological Storage. Published: IGES, Japan IPCC.

*2. **Waste Prevention Audit**—not directly pertinent to CCS*

*3. **Consideration of Waste Management Options**—not directly pertinent to CCS*

*4. **Chemical and Physical Properties**—characterization of the CO_2 stream*

*5. **Action list**—screening for acceptability of substances to be disposed, in this case the CO_2 stream including impurities.*

*6. **Site selection and Characterization**—both of the storage formation and of the marine area, drawing upon the IPCC SR, including evaluation of potential exposure to CO_2 and other substances mobilized by the CO_2, identification of leakage pathways and probabilities, modelling of the CO_2 behavior.*

*7. **Assessment of potential effects**—bringing all the above together into a risk assessment and producing an impact hypothesis.*

*8. **Monitoring and risk management**—to verify the site management and that permit conditions are being met, a detailed monitoring program defined from the results of the impact hypothesis, including a mitigation plan in the event of leakage.*

*9. **Permit and permit conditions**—the information required for and in a permit.*

Refinements added to the CO_2 Specific Guidelines included a further definition of the CO_2 stream which clarifies that substances can be added to assist CCS. "*the CO_2 stream, consisting of: .1 CO_2; .2 incidental associated substances derived from the source material and the capture and sequestration processes used: .1 source- and process-derived substances; and .2 added substances (i.e., substances added to the CO_2 stream to enable or improve the capture and sequestration processes)*" [IMO 2007, section 1.3].[284]

On CO_2 stream purity, the Scientific Group concluded that, rather than stipulating a generic standard for stream purity, given that the overall requirement is for environmental safety the levels of these impurities should be related to potential impacts on the integrity of storage and transport, and assessed on a case-by-case basis recognizing the natural variation in storage site characteristics (as in IPCC (2005)[285] and IPCC guidelines (2006)[286]) and different transport constructions. This principle is described in the Specific Guidelines (IMO 2007)[284] and is why the general phrase "*consist overwhelmingly of carbon dioxide*" is used in the legal amendment.

The Specific Guidelines provide guidance on permitting and permit contents. A key requirement identified is that permits (and permit applications) should contain information on the CO_2 stream composition, and a risk management plan which has itself to include: a monitoring plan (operational and long term) and reporting requirements; a mitigation and remediation plan (for in the event of leakage): and a site closure plan with post-closure monitoring (IMO 2007 section 9.1).[284] Permits should be reviewed at regular intervals and should take into account any changes identified from the monitoring and updated risk assessments.

8.2.1.1 Transboundary Issues under the London Protocol

The main issue for CCS at the London Protocol since the 2006 amendment is the topic of transboundary export of CO_2 for sub-seabed geological storage. The London Protocol Article 6 prohibits exports of wastes for dumping in the marine environment.

ARTICLE 6. EXPORT OF WASTES OR OTHER MATTER.

"Contracting Parties shall not allow the export of wastes or other matter to other countries for dumping or incineration at sea." (London Protocol 1996)[280]

This is intended to stop Parties exporting their waste to non-Parties so as to get around the London Protocol controls. However, this prohibits transboundary transport, i.e., export, of CO_2 for sub-seabed geological storage. There may well be a need for such export in the situations where a Party does not have sufficient suitable geological storage capacity but they still wish to use CCS to reduce emissions. In the 4th meeting of contracting parties to the Protocol (LP4) in October 2009 an amendment was adopted to remove this restriction (IMO 2009 resolution LP.3(4)).[286] The amendment requires that an agreement or arrangement has been entered into by countries concerned, which should include permitting responsibilities and, for export to non-parties, equivalent provisions as those required of Protocol Parties.

AMENDMENT TO ARTICLE 6 OF THE LONDON PROTOCOL

"2 Notwithstanding paragraph 1, the export of carbon dioxide streams for disposal in accordance with Annex 1 may occur, provided that an agreement or arrangement has been entered into by the countries concerned. Such an agreement or arrangement shall include:

2.1 confirmation and allocation of permitting responsibilities between the exporting and receiving countries, consistent with the provisions of this Protocol and other applicable international law; and

2.2 in the case of export to non-Contracting Parties, provisions at a minimum equivalent to those contained in this Protocol, including those relating to the issuance of permits and permit conditions for complying with the provisions of annex 2, to ensure that the agreement or arrangement does not derogate from the obligations of Contracting Parties under this Protocol to protect and preserve the marine environment.

A Contracting Party entering into such an agreement or arrangement shall notify it to the Organization." (IMO 2009)[286]

Work commenced to revise the CO_2 Specific Guidelines for the assessment of carbon dioxide streams for disposal into sub-seabed geological formations to take into account transboundary activities (export and migration). Through this work, it was decided that sub-seabed migration across national boundaries does not constitute export, and so was not prohibited by Article 6, but

[286] IMO 2009. On the Amendment of Article 6 of the London Protocol [CO_2 export amendment]. Resolution LP.3(4). 2009

was not covered by the CO_2 Specific Guidelines. The revised CO_2 Specific Guidelines were finalized and adopted on 2 November 2012 (IMO 2012 annex 8).[287]

The other transboundary aspect to be resolved is the development of guidance to determine the responsibilities of Parties in the case of export of CO_2, in particular if exported to a country that is not a party to the London Protocol. A new document "Guidance on the Implementation of Article 6.2 on the Export of CO_2 Streams for Disposal in Sub-seabed Geological Formations for the purpose of Sequestration" was produced (IMO 2013).[288] This sets out the responsibilities of Parties and the requirements of the agreements and arrangements which must be entered into by Parties who wish to undertake export of CO_2, including if to non-Parties, so as to ensure that the standard of requirements of the London Protocol on permitting CO_2 geological storage are maintained. In the case of a breach of an agreement or arrangement by a non-Contracting Party, the Contracting Party should "*engage in consultations to rectify*". In the case of a "*significant ongoing breach*" the Contracting Party is required to terminate the export (IMO 2013).[288] This new Guidance was adopted at the Annual Meeting on 18 October 2013, for use when the export amendment comes into force.

However there is one significant remaining transboundary aspect to be resolved. The export amendment adopted in 2009 to allow export of CO_2 for geological storage requires two thirds of Parties to ratify before it comes into force. This currently means 30 countries need to ratify it. To date just two have: Norway and UK. Emphasis and concern on the rate of this ratification was expressed by Mr. Koji Sekimizu, the IMO Secretary-General in his opening speech to the 2013 annual meeting of the London Convention and London Protocol (held at the International Maritime Organization in London from 14-18 October 2013 (LC35 and LP8).

"*The London Protocol currently is also the only global framework to regulate carbon capture and sequestration in sub-seabed geologic formations… …. However, it remains a serious concern that, to date, only two of the 43 London Protocol Parties have accepted the 2009 amendment, which is a long way from satisfying the entry-into-force requirements. The importance of securing its entry-into-force cannot be over-emphasized, if the threat from acidification of the oceans from climate change is to be minimized.*"[289]

It is understood by the authors' informal enquiries that just five further countries are working on their ratification at the moment, so at this rate it will take many years to come into force, and in the meantime London Protocol countries cannot export their CO_2 to another country for storage in

[287] IMO 2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-seabed Geological Formations.LP.7. LC 34/15, Annex 8. 2012 [aka Revised CO_2 Specific Guidelines or Revised CO_2 Sequestration Guidelines]

[288] IMO 2013. Guidance on the Implementation of Article 6.2 on the Export of CO_2 Streams for Disposal in Sub-seabed Geological Formations for the Purpose of Sequestration. LC 35/15 Annex 6. 2013

[289] Sekimizu, K., 2013. Address of the IMO Secretary-General at the opening of the thirty-fifth meeting of Contracting Parties to the London Convention and the eighth meeting of Contracting Parties to the London Protocol, London, 14 October, 2013. http://www.imo.org/en/MediaCentre/SecretaryGeneral/Secretary-GeneralsSpeechesToMeetings/Pages/LC35LP8.aspx

the marine environment. The exception is if the CO_2 is a purpose other than dumping, such as for enhanced oil recovery.

8.2.2 OSPAR

OSPAR (1992)[290] is the convention protecting the marine environment in the North East Atlantic, with 15 nations and the EC as Parties. Similarly to the London Protocol, OSPAR was drafted without CCS in mind. Like the London Protocol, OSPAR specifies what is allowed to be dumped in its Annexes, and is considered more restrictive than the London Protocol. In the light of the work on the London Protocol amendment, in 2006 OSPAR started legal work to consider its own amendment, and started a technical group to assess and refine for OSPAR purposes the London RAMF. This work resulted in guidance called the OSPAR Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (known as the FRAM) (OSPAR 2007a).[291]

The structure of the OSPAR FRAM mirrors that of the London RAMF, with the same purpose. The principles established for CCS in London were also repeated in the FRAM. Again, the focus was on geological storage and explicitly not on storage in coal beds, basalts, oil and gas shales, or salt caverns. Refinements included the addition of an 'impact hypothesis' in the risk characterization, providing more information on monitoring requirements, and identification of areas benefiting from further research.

Two amendments were required, for OSPAR's Annex II dealing with dumping and for Annex III dealing with offshore sources. These amendments were proposed in 2007 by Norway and co-sponsored by UK, Netherlands, and France. As well as the FRAM, guidelines were produced on how to use the FRAM, these were the OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (known as the OSPAR Guidelines), which included the FRAM as an integral annex (OSPAR 2007b).[292]

OSPAR was amended in June 2007 by consensus. The legal amendments were similar to London's but with an additional condition:

"CO_2 streams from CO_2 capture processes for storage...provided:

- *Into a sub-soil geological formation*
- *Consist overwhelmingly of CO_2. May contain incidental associated substances derived from the source material and capture and sequestration processes used*

[290] OSPAR (1992). Convention for the Protection of the Marine Environment of the North-East Atlantic. (OSPAR). 1992. More information available at www.ospar.org

[291] OSPAR 2007a. Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formation (FRAM). Annex 7 in OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations. Summary Record OSPAR 07/24/1-E Annex 7 (2007).

[292] OSPAR 2007b. Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations. Summary Record OSPAR 07/24/1-E Annex 7 (2007)

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- *No wastes or other matter are added for the purpose of disposal*
- *They are intended to be retained permanently and will not lead to significant adverse consequences for the marine environment, human health and other users "(OSPAR 2007c)*[293]

The permanent retention point means that sites with even low enough levels of leakage for climate benefit cannot be used.

At the same time, OSPAR Parties adopted a 'Decision' (a legal decision) to make use of the OSPAR Guidelines obligatory (OSPAR 2007d)[294] when issuing permits for geological storage of CO_2. In the London Protocol, the similar guidelines are for guidance only (though the London Protocol includes more detailed provisions on the issuing of permits within an overarching annex). This OSPAR Decision 2007/2 (OSPAR 2007d)[294] includes permit requirements similar to those in the London Specific Guidelines, but in more detail.

Any permit or approval issued shall contain at least:

1. a description of the operation, including injection rates;

2. the planned types, amounts and sources of the CO_2 streams, including incidental associated substances, to be stored in the geological formation;

3. the location of the injection facility;

4. characteristics of the geological formations

5. the methods of transport of the CO_2 stream;

6. a risk management plan that includes:

i. monitoring and reporting requirements ;

ii. mitigation and remediation options <u>*including*</u> *the pre-closure phases; and*

iii. a requirement for a site closure plan, including a description of post-closure monitoring and mitigation and remediation options; monitoring shall continue until there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level. [OSPAR 2007d Section 3.2.6][294]

The point in part 6.iii on monitoring means that monitoring may cease when confidence exists in the security of the CO_2 storage, reflecting the IPCC GHG Guidelines (IPCC 2006). The OSPAR Decision also included the requirement for reporting, including post-closure reports, and a reporting template (OSPAR 2007d Appendix 1).[294]

In addition, at the same meeting, OSPAR adopted another Decision to adopt a German proposal to prohibit ocean storage *"The placement of carbon dioxide streams in the water column or on the*

[293] OSPAR 2007c. Amendments of Annex II and Annex III to the Convention in relation to the Storage of Carbon Dioxide Streams in Geological Formations. Summary Record OSPAR 07/24/1-E Annex 4. (2007)

[294] OSPAR 2007d. OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations. Summary Record OSPAR 07/24/1-E Annex 6. (2007)

seabed is prohibited" (OSPAR 2007e).[295] Thus ruling out ocean storage for OSPAR countries, unless for experimental purposes.

In terms of timescales, the OSPAR Decision to use the OSPAR Guidelines, and the Decision on ocean storage, came into force on 15 January 2008, for all CO_2 geological storage projects in the marine environment except those for enhanced oil recovery or from normal operations or experimental purposes, which fall outside the OSPAR cover. The legal amendments to remove the prohibitions came into force after seven OSPAR Parties ratified them, which was achieved on 23 July 2011.

Note that OSPAR does not have the export prohibition on wastes. Note also that both these marine treaties do not deal with long term liability.

8.3 Examples of Specific National Regulatory Requirements

8.3.1 Japanese regulations

Prior to her ratification of the London Protocol in 2007, Japan amended the Act on Prevention of Marine Pollution and Maritime Disaster to set out a regulatory framework for CO_2 sub-seabed storage in a way of complying with the Protocol. The amendments prohibit dumping in the sub-seabed in addition to that in the water column and exempt CO_2 sub-seabed disposal or storage if permitted by the Environment Minister. The Act regulates CO_2 disposal not only at sea but also from the land, for example, through an inclined well with its wellhead onshore, which is beyond the Protocol. To obtain a permit, those who plan to dispose CO_2 under the seabed are required to submit to the Minister such documents as a project plan and a CO_2 monitoring plan. The Minister may issue a permit if determining, for example, that the way of storing CO_2 stream will not harm the conservation of the marine environment around the storage site and that there are no other appropriate ways of disposal available. More detail requirements are set out in a cabinet order, ordinances and a notification of the Ministry of the Environment (MOE).

The major documents of an application are, as mentioned above, a project plan and a CO_2 monitoring plan. The MOE ordinance for dumping permits requires the monitoring plan to be developed for three cases: for normal times, for CO_2 leak possibly taking place and for leaking or nearly leaking. The MOE notification categorizes those to be monitored, which are the same for the three cases: injected/ stored CO_2, reservoirs, seawater chemicals, marine organisms and ecosystems, and marine utilization such as marine leisure and fishery. The ordinance also requires applicants to submit an environmental impact assessment (EIA) report as an attachment to a permit application. To complete the EIA report, applicants need to set up CO_2 leak scenarios; project locations, spatial extent and volume of CO_2 leakage based on the scenarios; identify those to be affected by the projected leakage such as marine organisms and the marine ecosystems; acquire

[295] OSPAR 2007e. OSPAR Decision 2007/1 to Prohibit the Storage of Carbon Dioxide Streams in the Water Column or on the Sea-bed. Summary Record OSPAR 07/24/1-E Annex 5. (2007)

baseline data of the potentially affected; and assess the potential impacts of the assume leakage on those.

The Act and its related legal orders were set out under a concept not to promote CCS but to regulate CCS. There are, therefore, a couple of stipulations which may need to be amended for wider CCS deployment in future. An example is that the regulations require an applicant to renew a permit every 5 years or less, but do not specify the end of the renewals. This implies that the storage operator should continue the renewals forever and keep on monitoring the injected CO_2 and the marine environment for an indefinite period. MOE has investigated appropriate conditions to allow operators terminating monitoring but such conditions are not incorporated legally at present. Another example is specifications for CO_2 stream allowed to be injected. The orders provides that CO_2 should be captured by amine and be a concentration of 99 vol% or more (the threshold of concentration is relaxed to 98 vol% for hydrogen production for oil refinery) on the assumption that amine is the capture technology most likely to be adopted in Japan. The regulator claims that they will amend stipulations when other promising technologies emerge, but anyway the current law does not allow oxyfuel combustion capture and widely-used pre combustion capture such as Selexol and Rectisol in Japan.

The regulations will be applied for the first time to a full-chain demonstration project funded by the Ministry of Economy, Trade and Industry (METI). The project takes place in Tomakomai, Hokkaido and plans to capture more than 100 thousand t of CO_2 per year from a hydrogen plant and inject the CO_2 to offshore reservoirs for 3 years, commencing in 2016. The project is exempted from the London Protocol in that CO_2 will be injected onshore with inclined wells. However, because the Japanese Government intends to report the project as that complying with the CO_2 Specific Guidelines under the Protocol to IMO and the contracting parties, the project will be recognized as the world-first CCS project to be operated under the framework of the Protocol once operated.

8.3.2 U.S. regulations

Regulation of future offshore sub-seabed GS of CO_2 in the United States will be the responsibility of two federal entities, the U.S. Department of Interior (DOI) and the U.S. Environmental Protection Agency (EPA). The area under DOI jurisdiction is the Outer Continental Shelf (OCS), which is that portion of the United States offshore from the seaward boundary of State submerged lands to the outer edge of the Exclusive Economic Zone (200 nautical miles [nmi] [370 km]). EPA will have jurisdiction over sub-seabed CO_2 GS in State submerged lands; these extend from shore line seaward to a distance of either 9 nmi (16.7 km) (Texas and west coast of Florida) or 3 nmi (5.6 km).

The DOI will have jurisdiction over sub-seabed CO_2 GS within the largest offshore portion of the United States, meaning those portions of the OCS not under drilling moratoria.[296] However, regulations specific to CO_2 sub-seabed GS have not yet been written. Through the Bureau of Safety

[296] U.S. Drilling Moratoria: http://www.boem.gov/Areas-Under-Moratoria/

and Environmental Enforcement (BSEE) and Bureau of Ocean Energy Management (BOEM) DOI already regulates offshore oil and gas activity on the OCS under the authority of the Outer Continental Shelf Lands Act.[297] This regulatory responsibility includes secondary and tertiary oil recovery, and by default EOR using CO_2. The current rules focus on resource recovery operations; regulations for monitoring to demonstrate that CO_2 injected for EOR is remaining in the deep sub-seabed will be needed if operators want to claim CO_2 storage credit.

The OCSLA was amended in 2005 to also give DOI authority to establish regulations for renewable energy resource recovery and other forms of energy and marine related uses of the OCS. DOI and BOEM have determined that they have authority to regulate GS of CO_2 generated from coal-fired power plants. They have not yet issued an opinion on whether they will also have authority to regulate GS for CO_2 generated by and captured from other types of industrial sources.

The Bureau of Economic Geology (BEG) at The University of Texas at Austin is working with the BOEM under funding from the National Oceanic Partnership Program[298] to provide (1) an analysis of existing BSEE and BOEM regulations that could be adapted to sub-seabed CO_2 GS, (2) an online EndNote database of pertinent existing manuals and guidance documents, and published literature, and (3) a report on Best Management Practices and Data Gap Analysis for Sub-seabed Geologic Carbon Dioxide Sequestration. This report is nearly ready for external review and will be finalized and submitted to BOEM in September 2015. Further discussion of how existing BSEE and BOEM regulations may be adapted to offshore GS, is contained in an interim report associated with BEG's BOEM project.[299]

The EPA has jurisdiction over onshore GS of CO_2 through two U.S. federal laws, the Clean Air Act (CAA)[300] and the Safe Drinking Water Act (SDWA).[301] The EPA, through its Office of Air and Radiation, is responsible for regulations to protect the public from air pollution. In 2007, the U.S. Supreme Court included CO_2 as an atmospheric pollutant the EPA must regulate. As a result EPA established the Greenhouse Gas Reporting program and in 2009 published regulations for industrial emitters of CO_2.[302] The association of this program to offshore CO_2 GS is through rules in its Subpart RR—Geologic Sequestration of Carbon Dioxide.[303] Certain Subpart RR rules require operators seeking to avoid future CO_2 emissions penalties through geologic sequestration

[297] OCSLA: http://www.boem.gov/Outer-Continental-Shelf-Lands-Act/

[298] National Oceanic Partnership Program: http://www.nopp.org/

[299] Smyth, R. C. and Thomas, P. G., III, 2013, Analysis of applicability of existing BOEM/BSEE regulations to offshore sub-seabed geologic sequestration of carbon dioxide: unpublished BEG interim contract report, 30 p.

[300] Clean Air Act: http://www.epa.gov/air/caa/

[301] Safe Drinking Water Act: http://water.epa.gov/lawsregs/rulesregs/sdwa/index.cfm

[302] Greenhouse Gas Reporting Program: http://www.epa.gov/ghgreporting/

[303] Subpart RR of the GHGRP: http://www.epa.gov/ghgreporting/reporters/subpart/rr.html

to follow an approved plan for monitoring, reporting, and verification (MRV). Such operations located on State submerged lands will be subject to EPA GHGRP Subpart RR.

Under the SDWA, EPA's Office of Water regulates protection of drinking water resources. The program most applicable to CO_2 GS is Underground Injection Control (UIC).[304] UIC has defined multiple classes of injection wells, each with their own set of rules. For example, EPA UIC Class I well rules apply to industrial and municipal waste disposal wells. Injection of CO_2 for EOR falls under EPA UIC Class II rules. In 2010, EPA published regulations for newly established UIC Class VI wells, which are wells used to inject CO_2 for long-term geologic storage without EOR. Class VI well rules include specific requirements for MVA of injectate-CO_2. Again, the purpose of EPA's UIC program is to protect drinking water resources. These regulations should apply in State submerged lands underlain by underground sources of drinking water (USDW),[305] or where sub-seabed stratigraphic units in hydraulic connection with onshore USDWs are present.

8.4 Implications of Regulatory Requirements on Technology Development

The international regulations were drafted in consultation with technical expertise on CO_2 geological storage, with the intention that they did not place unrealistic requirements on the science, the operators or the regulators. This means that they are based upon the level of knowledge and technology development that existed in 2004-2008. With the emphasis on protection of the marine environment, there is an emphasis on monitoring techniques for both leak detection and impact assessment, as well as for environmental baseline measurements. There has since been much work in developing such techniques, and some have been demonstrated at offshore sites such as in Europe.

Monitoring strategies may need to be devised to cover large areas, typically tens to hundreds of square km and also achieve accurate measurement and characterization possibly over lengthy periods. Limited spatial coverage could lead to the risk that anomalies remain undetected or are only detected after a lengthy period of time. Search areas could be narrowed down by the integration of information from deeper-focused monitoring, such as 3D seismics which can identify migration pathways, with shallow surface monitoring such as acoustic detection.

Deep-focused monitoring relies heavily on established hydrocarbon industry tools which are mature. There is scope for improving some of these technologies and related data processing and interpretation for CO_2 storage. The quantification of CO_2 within a reservoir still remains a challenge.

Shallow-focused monitoring is less advanced compared with deep focused monitoring, but systems are being developed and demonstrated. New marine sensor and existing underwater platform technology such as AUVs and mini-ROVs enable deployment and observation over large areas at potentially relatively low cost. Seafloor and ocean monitoring technologies can detect both dissolved phase CO_2 and precursor fluids (using chemical analysis) and gas phase CO_2. AUV

[304] Underground Injection Control Program: http://water.epa.gov/type/groundwater/uic/index.cfm

[305] Underground sources of drinking water definition: http://water.epa.gov/type/groundwater/uic/glossary.cfm

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technology capable of long-range deployment needs to be developed so that the AUV can be tracked transmit data via a satellite communications system. Real-time data retrieval and navigation will enable onshore operators to modify or refine surveys without costly intervention using a survey vessel. Further development in integrated in situ sensors has been underway over the last 5 years. The quantification of leakage at the seabed remains a technical challenge.

The capabilities to predict the behavior of marine systems using models need to be improved. Advances are needed so that systems can simulate leakage in the context of natural variability by combining both pelagic and benthic dispersion and chemistry, including carbonate and redox processes. Models that can simulate large scale dispersion of multi-phase plumes whilst simultaneously simulating tidally-induced dispersion in the near- and far-field also need to be developed.[306]

8.5 Implications of Technology Development on Regulations (i.e., better modeling/simulation tools, etc. and influence on regulations)

There have been significant developments in the regulation of CO_2 geological storage offshore. This section has described the main developments internationally and for Japan and the United States. These regulations have created an enabling regulatory situation for CCS offshore whilst ensuring the protection of the marine environment and other resources.

These regulations, particularly the international ones, were among the first dedicated CCS regulations to be developed. Experience and assessment of their suitability with application with projects would be beneficial. There have also been significant developments in technologies and knowledge since the period these regulations were developed, particularly in the areas of monitoring and environmental assessment, with testing and demonstration of these developments in Europe, Japan, and the United States. It is recommended that the knowledge gained through the development and application of these regulations, and the relevant technical knowledge and developments since, are shared with other countries who may be interested in offshore CCS.

[306] IEAGHG, “Offshore Monitoring for CCS Projects”, Report 2015/02.

9 Summary and Recommendations

Offshore storage has been demonstrated by the Sleipner project for nearly 20 years and much has been learned from this effort. Additionally, the oil and gas industry has developed significant toolsets and capabilities for offshore hydrocarbon recovery and transport. However, there are also significant opportunities to increase our understanding of offshore CO_2 storage. Some of these opportunities include: storage capacity assessments, infrastructure, monitoring and modeling, and understanding of environmental impacts and dynamics of CO_2 dispersion in ocean environment.

There is a growing wealth of research, development and practical experiences that are specific to, or relevant for, CO_2 storage offshore, as described in the preceding chapters, but this expertise is familiar only to a few specific countries around the world. However there is also significant global potential for offshore CO_2 storage, and countries who are not yet active but may become interested in offshore storage, would benefit from knowledge sharing from these existing experiences and expertise. Such international knowledge sharing would be facilitated by international workshops and by international collaborative projects. The CSLF is very well-positioned to encourage and support such knowledge-sharing activities.

Storage Capacity Assessments

Global storage capacity assessments at the national level are currently inadequate. These assessments are typically high risk and involve long lead times to prove storage capacity and support the development of first-wave or even second-wave CCS projects. The long lead time (in the range of 7–10 years) means that storage qualification defines the start-up time of a CCS project. There are also cost implications. For example, although the cost of storage is typically considered to be lower than that of capture, one 'dry' hole (i.e., into a formation that proves not to be a good storage resource) would significantly increase the cost of storage.

Recommendation: It would help prospective CCS stakeholders if public-private partnerships were developed to provide a number of pre-qualified storage locations.[307] For such locations, all preparatory work, including the documents for a storage permit application could be made available to reduce the uncertainty regarding the availability of storage. This would support both the storage and the transport elements of CCS projects.

It is recommended that a more thorough evaluation of the geologic storage aspects of many basins be pursued. It is also recommended that an increased level of knowledge sharing and discussion be implemented among the international community to outline the potential for international collaboration in offshore storage.

Transport Infrastructure

Technology solutions for CO_2 transport exist and have shown to be robust during decades of operation. Offshore CO_2 transportation is more limited, but can benefit from substantial

[307] This is sometimes referred to as 'bankable' storage capacity.

operational experience from natural gas pipelines. Compared with onshore pipeline transportation, offshore CO_2 transport will probably be more expensive, but there are also some distinct advantages, such as less exposure to issues around routing, shipping is a mode of transport with large flexibility in a start-up phase and to tie in smaller CO_2 sources, and a more stable physical environment.

Recommendation*:* To realize the international ambitions to mitigate global warming, the CO_2 transportation infrastructure must increase significantly and will be an important contributor to the overall costs for CCS. Hence, optimization of current practices is important, on areas such as CO_2 product specifications and sharing of infrastructure to optimize utilization.

Additionally, during the pilot and demonstration phase of CCS, CO_2 volumes will be relatively small. However, these projects could be developing the first elements of the large-scale infrastructure, if sufficient incentive is given to oversize the components of the transport infrastructure. Especially during the early phase of CCS, public-private partnership is essential to generate these large infrastructural works.

An increase in the available financial incentives for (offshore) CCS project is needed to increase the speed of development of offshore CCS. Funding mechanisms should consider funding operational costs, as well as up-front investments.

Offshore CO_2-EOR

Currently, the only offshore CO_2-EOR project that exists is the Lula project in Brazil. However, offshore CO_2-EOR is seen as a way to catalyze storage opportunities and build the necessary infrastructure networks. One of the barriers reported widely for offshore CO_2-EOR projects is the investment required for the modification of platform and installations, and the lost revenue during modification.

Recommendation: Recent advances in subsea separation and processing could extend the current level of utilization of sea bottom equipment to also include the handling of CO_2 streams. By moving equipment required to separate and condition the CO_2 to the seafloor, modifications to the platform can be minimized. It is recommended that RD&D activities explore opportunities to leverage existing infrastructure and field test advances in subsea separation and processing equipment.

Understanding of CO_2 Impacts on the Subsea Environment

Over the last decade, a significant body of research into the impacts of high CO_2 concentrations on marine systems has matured, driven directly by CCS but also by concerns regarding ocean acidification. Much of this work has concentrated on physiological impacts and has utilized laboratory scale manipulations. However both natural analogues, typically where volcanic CO_2 is emitted at the seafloor, and more recently a controlled release experiment, where CO_2 was deliberately injected into the seabed, have been used to study the synergistic impacts driven by a combination of hydrodynamics, ecosystem interactions, behavior and physiological responses. The main outcome from these real world experiments is a glimpse of the complexity of impacts and the challenges to efficient monitoring, in particular the requirement for a comprehensive understanding of natural variability necessary to correctly identify and quantify non-natural change. For example, it has been observed that carbonates, naturally present in some sediments undergo dissolution in the presence of excess CO_2, reducing the presence of gas at the seafloor, some of the chemical parameters and biological impacts. However sediment carbonate is finite and once exhausted a step change in detectability and impact is likely.

Recommendation: Leverage the existing body of knowledge to expand R&D efforts to diverse geologic storage sites. Specific challenges arising from existing work are to understand the buffering potential of sediments, and the impact of longer term exposures.

It is also recommended to expand upon modeling efforts to understand CO2 dispersion in an ocean environment. Whilst the primary driver of the spatial extent of detectability and impact is the leakage rate, many other factors such as depth, bubble size, current speed, tidal mixing and topography are shown to have a large influence on dispersal. Existing models are robust, but limited in that they generally cannot deal with very fine scales (≈1m) which are necessary for the correct treatment of small leak scenarios at the same time as accurately defining regional scale mixing processes, necessary for the correct estimation of dispersion. Model development of marine systems is required to improve their predictive capabilities. Advances are needed so that systems can simulate leakage in the context of natural variability by combing both pelagic and benthic dispersion and chemistry, including carbonate and redox processes. There is also a need to develop models that can simulate large scale dispersion of multi-phase plumes whilst simultaneously simulating tidally-induced dispersion in the near and far field.

Monitoring Technology Development

Monitoring strategies may need to be devised to cover large areas, typically tens to hundreds of square km, and also achieve accurate measurement, characterization and repeatability possibly over lengthy periods. Limited spatial coverage could lead to the risk that anomalies remain undetected or are only detected after a lengthy period of time. Search areas could be narrowed down by the integration of information from deeper-focused monitoring, such as 3D seismic which can identify migration pathways, with shallow surface monitoring such as acoustic detection.

Recommendation: Deep-focused monitoring relies heavily on established hydrocarbon industry tools which are mature. There is scope for improving some of these technologies and related data processing and interpretation for CO_2 storage. The quantification of CO_2 distribution within a reservoir still remains a challenge.

Shallow-focused monitoring is less advanced compared with deep focused monitoring, but systems are being developed and demonstrated. New marine sensor and existing underwater platform technology such as AUVs and mini-ROVs enable deployment and observation over large areas at potentially relatively low cost. Seafloor and ocean monitoring technologies can detect both dissolved phase CO_2 and precursor fluids (using chemical analysis) and gas phase CO_2. AUV technology capable of long-range deployment needs to be developed so that the AUV can be tracked transmit data via a satellite communications system. Real-time data retrieval and navigation will enable onshore operators to modify or refine surveys without costly intervention using a survey vessel. Further development in integrated in situ sensors has been underway over the last 5 years. The quantification of leakage at the seabed remains a technical challenge.

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10 Appendix

Tables from IEAGHG Offshore Monitoring Report

Table A1 Surface seismic methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Streamer—3D seismic	High detection and resolution capabilities. Data suitable for advance analysis especially the investigation of reservoir properties and plume tracking	Routine deployment, robust and mature but requires large unobstructed areas of sea Detection threshold depends on geometry of CO_2 accumulation	Sleipner, Snøhvit. Planned for Goldeneye, ROAD, Tomakomai* (Retrievable OBC 3D seismic)	Can provide robust and uniform spatial surveillance of storage complexes. Can detect small changes in fluid content and therefore useful for leakage detection. Changes in time-lapse seismic images can detect small quantities of CO_2.	Ability to track CO_2 plumes is useful to corroborate model predictions and can be used to refine or modify them. Plume mobility and storage efficiency can be checked. Measured time-shifts can reveal indicative pressure changes in reservoirs.	£10M+ depending on survey area, specification, and locality. Processing time up to £1M in computing time	Lack of significant azimuthal variation in wave propagation which limits azimuthal analysis for evaluation of anisotropy and geomechanical integrity. Interpretation and detection of CO_2 relies on good repeatability which may not always occur.

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Streamer 2D seismic	High detection and resolution capabilities similar to 3D seismic. Star survey configuration can provide image of plume spread.	More compact compared to 3D. Time-lapse is reputedly poor.	Sleipner, Tomakomai (OBC 2D seismic)			<£1m depending on survey area, specification, locality	Lack of 3D migration in processing precludes optimum imaging of some subsurface structures.
Streamer—P Cable seismic	High resolution 3D seismic system suited to shallow sections (<1,000 m) therefore useful for imaging shallow overburden. High spatial and temporal resolution possible Useful for 3D mapping of structures especially faults.	Relatively compact and short than 3D and 2D configurations gives high maneuverability.	Snøhvit, Gulf of Mexico	Useful for containment risk assessment and leakage monitoring by tracking CO_2 migration above storage complexes		<£1m depending on survey area, specification, locality	Sea bed multiple can obscure important features. Vulnerable to reduced performance in poor sea conditions.

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Chirps, boomers and pingers	Designed for very high resolution surface seismic surveys direct detection of bubble-streams may be possible in favorable circumstances.	Can be deployed from small site-survey vessels. AUV systems can be equipped with Chirp transducers. AUV survey has detected clear images of natural gas pockets in central North Sea	Sleipner, planned for Goldeneye			<£100k	Designed for shallow surface surveys. AUV based systems have limited penetration due to lower power availability.

Table A2 Ocean bottom seismic methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
OBN and OBC	As static observation data recorders these devices can provide full azimuth coverage with multicomponent sensors with p and s-wave recording for geomechanical and isotropy characterization. Long-term recording is useful for detecting natural and induce seismicity	Can provided information in close proximity to platforms	OBN planned at Goldeneye OBC planned at Tomakomai			£10M+ but unlike streamer surveys there is a high initial cost to set up the system and relatively low costs for repeat surveys.	Vulnerability to trawling operations. Limited spatial sampling density compared with streamer surveys.

Table A3 Downhole seismic methods

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
4D VSP (Vertical seismic profiling)	High resolution imaging of near-wellbore region 10s–100s meters radius	Permanent downhole sensors allow for cost-effective time-lapse imaging. Data processing can be complex. Fiber-optic acoustic cable might improve reliability.	Goldeneye (under consideration)				Coverage is non-uniform (spatially variable offsets and azimuths) which can make interpretation difficult. Time-lapse repeatability is uncertain. Reliability of sensors is a key issue.
Passive seismic monitoring	Allows continuous monitoring for microseismic events	Deployment in one or more shallow wells (<200m). Microseismic events can be used to identify structures such as faults and fractures. Important to establish natural background seismicity to distinguish events related to CO_2 injection and migration.	Planned for ROAD and Tomakomai Considered for Goldeneye		Important to establish natural background seismicity to distinguish events related to CO_2 injection and migration.	High initial costs required for deployment. Maintenance costs could also be high	Sensor reliability can make the method vulnerable leading to potentially limited signal records.

Table A4 Potential field methods

Method	Capabilities	Practicalities	Deployment	Cost	Limitations
Sea bottom gravimetry	Directly measures mass change within reservoirs which is a conformance-related parameter	Offshore deployment is logistically complex requiring ROV and boat support to emplace concrete benchmarks	Sleipner	Low compared to 3D streamer surveys. A 50 station near-shore survey would cost ≈£1M.	
CSEM	Can provide complementary information to seismics. Method is sensitive to fluid saturation at higher CO_2 saturation levels	Offshore deployment is logistically complex	Sleipner	Costs high and comparable with offshore 3D seismics.	The technique is severely hampered in shallow water (<300m).

Table A5 Downhole measurements

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Downhole pressure and temperature	Downhole gauges are capable of detecting very small temperature and pressure changes which are a primary method for monitoring injected CO_2 physical properties and reservoir performance. Position of gauge across permeable units can give indications of out-of-reservoir migration.	Deployment is a requirement under the EU Storage Directive, Long-term surveillance needs to take account of instrument drift and reliability.	Snøhvit, K12-B. Planned for Goldeneye, ROAD, Tomakomai	Key for controlling geomechanical integrity of the reservoir and caprock. Any unexpected pressure reduction in the reservoir could indicate potential leakage.	Essential for monitoring fluid flow performance and model calibration demonstrating reservoir permeability, storage capacity and geomechanical stability.	Relatively low <£100 plus installation and retrieval of gauges	

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Geophysical logging	Standard oilfield technique used for calculating CO_2 saturation. Provided there is a good baseline survey, repeat surveys can be used to calculate CO_2 saturations	Downhole logging is dependent on access to wellbores which might be restricted. Obstructions such as scale accumulation may preclude logging.	Planned at ROAD and Goldeneye		Pulsed neutron capture logging is planned for Goldeneye to acquire a good baseline and quantify CO_2 thickness interval.	Cost varies depending on the suite of logs run	

Table A5 Downhole measurements

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Wellbore integrity monitoring	Standard oilfield technique including cement bond logs used to check integrity of the cased wellbore. Quality and availability of legacy data from abandoned wells may limit effectiveness of integrity checks. Ultrasonic imaging, Multi-finger calliper and Electromagnetic imaging, downhole video and real time borehole stress and tubing/ casing deformation imaging are used to check casing and tubing integrity.	Techniques is reliant on access to wells and different operations. Build-up of scale can cause problems by obstructing logging tools.	K12-B, planned at ROAD and Goldeneye		Wellbore integrity is essential for long-term CO_2 storage security by preventing leakage. At Goldeneye logs will be run prior to injection to establish a baseline. Integrity will be checked initially in year three and then every 5 years until injection is completed.	Cost varies depending on the suite of logs run	

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Downhole fluid sampling.	Analyses of reservoir fluids can yield pCO_2,pH HCO_3^-, dissolved gases, stable isotopes and tracers	Sampling should be carried out at ideally at reservoir pressure. Requires access to specific reservoir zones. U-tube is deployed onshore but does not have safety certification for offshore deployment.	K12-B planned at Goldeneye		At K12-B analyses of gas samples from two production wells revealed heterogeneous nature of the reservoir. Wireline downhole sampling proposed for Goldeneye.	Onshore cost per sample ≈£5-10k per sample.	Accuracy of breakthrough timing depends on temporal sampling frequency.

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Chemical tracers and gas analyses	Tracers and isotopic signatures can help to identify CO_2 origin and monitor migration or potential leakage.	Tracers can be injected in a pulse or continuously. Tracers can be detected in extremely small quantities using gas chromatography or mass spectrometry.	K12-B planned at Goldeneye	At Goldeneye use of tracers is being considered to distinguish between natural CO_2 being emitted from the sea bed and CO_2 from the storage complex.	Tracer studies at K12-B showed breakthrough occurred at two producer wells after 130 days and 463 days depending on distance from the injector. Differing CO_2 and CH_4 solubilities and insoluble tracers mean these breakthrough rates may not reflect real CO_2 migration rates.	Noble gases analyses are ≈£350 compared with £125 for SF_6	

Table A6 Sub-sea monitoring

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Seabed and water column imaging.	Active acoustic techniques can be effective at detecting gas fluxes. Multibeam echosounders (MBES) can be used for 3D bathymetric surveys. In time-lapse mode method could be used to detect slight changes in seafloor that might be caused by CO_2 leakage. Acoustic bubble detection can identify bubble releases	These are established techniques that can be carried out by a survey vessel with multiple imaging systems. This is a cost-effective means of surveying large areas of sea bed. AUV and ROV systems can operate closer to the seabed, the scale and operational duration of surveys is limited the size of the device.	Pervious side-scan sonar, single beam and multibeam echosounding and pinger sea bottom profiles were conducted. Surveys at Sleipner and Snøhvit. Pockmarks were clearly identified but no bubble streams. Acoustic bubble detection is planned at ROAD. A MBES plus side-scan sonar is planned for Goldeneye			Surveys 10 km2 cost ≈£100k - £200k but cost efficiencies are possible if multiple techniques are carried out.	There is a trade-off between the scale of the survey area and the ability to survey the seafloor from an AUV. Static seabed sensors can achieve high resolutions but over smaller fixed areas. However, they are generally more costly to install, maintain and retrieve compared to mobile equipment.

Method	**Capabilities**	**Practicalities**	**Deployment**	**Containment Monitoring**	**Conformance**	**Cost**	**Limitations**
Underwater video	Detection and recording of high definition images of bubbles and other features such as bacterial mats and biota behaviors which may give an indication of CO_2	Image quality can vary depending on water quality and height above seabed.	Sleipner			≈£1k-10k	A highly qualitative technique with a poor ability to resolve the size and shape of bubbles.
Seabed displacement monitoring	Vertical displacements of the seabed can be indicative of pressure changes in reservoirs. GPS system could measure rates with a accuracy range of 1-5mm.	Sensor networks on seafloor that use acoustic ranging techniques, pressure gauges or tiltmeters can give very accurate measurements of seabed movement	Planned for Goldeneye. Single GPS station mounted on a platform.	Monitoring subsidence or uplift can provide evidence of containment and conformance.		≈£1k-10k for single GPS station mounted on a platform.	

Table A6 Sub-sea monitoring (cont.)

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Geochemical water column sampling.	Water column measurements using Conductivity, Temperature and Depth (CTD) probes in combination with pH pCO_2, dissolved O_2, inorganic and organic carbon, nitrogen, phosphate, Eh, salinity can be sued to detect anomalous chemistry.	CTD probes can be conducted from survey ships. Continuous measurements can be made. Interpreting a leakage signal above background measurements can be extremely challenging. Baseline measurements ideally need to reflect a degree of natural variability.	Sleipner and Snøhvit, and planned at Goldeneye (permanently attached to platform) and Tomakomai. A survey over a period 2011 -2013 above Sleipner found no evidence of CO_2.			≈£1k–10k for a survey when deployed from a vessel conducting other surveys	The density, timing and the vertical spacing separation of surveys may mean small leakage plumes could remain undetected depending on plume dispersion.

Method	Capabilities	Practicalities	Deployment	Containment Monitoring	Conformance	Cost	Limitations
Sediment sampling	Time-lapse sediment sampling can be used to detect changes in sediment, pore fluid that could indicate CO_2 leakage. Detecting CO_2 leak induced changes above background requires a good understanding of natural variability	Quality of sample depends on substrate and whether core has retained pore fluid at the original in situ pressure. Specialist vibrocorer equipment is required.	Sleipner and Snøhvit, and planned at Goldeneye) and Tomakomai. Repeat surveys will be conducted to detect possible changes induced by CO_2 leakage.		Seabed sediment samples from Goldeneye will be analyzed for a suite of dissolved gases to provide a background baseline.	£5k / day for equipment deployment and excluding ship time.	
Ecosystem response monitoring	Time-lapse sediment sampling can be used to detect changes in benthic flora and fauna caused by elevated CO_2 concentrations either as a gas phase or by a reduction in pH. Avoidance behavior needs to be distinguished by changes induced by natural variability	Species density and variety can be recorded with underwater video.	At Goldeneye ecosystem sampling using Van Veen Grab is planned.			≈£100s per sample excluding processing and organism identification	Most effective biomarker species have not yet established.

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-T-2015-07
28 September 2015

TECHNICAL GROUP

Potential New Action Plan Activities

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.

At the Regina meeting in June 2015, a working group was formed to develop and prioritize potential new Action Plan activities. This paper represents the report from the working group.

Action Requested

The Technical Group is requested to review the working group's report on potential new Action Plan activities.

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CSLF Work Group on New Opportunities - Summary

Highest Priority Task Activities

Geo-steering and pressure management techniques and applications. Brine production is considered a potential mechanism for "geo-steering" of carbon dioxide (CO_2) plume, and reservoir and pressure management. This study will investigate novel methods such as brine extraction for pressure and reservoir management in carbon storage operations.

Bioenergy with carbon capture and storage (CCS). Biomass power generation or biomass to fuels has the potential for negative carbon emissions when combined with CCS. This study will look at the current global status of biomass applications and the potential application of CCS and technology gaps or challenges.

Offshore EOR. Offshore CO_2-EOR has not really taken off. Presently, only one offshore EOR project is using CO_2 as driver (Lula in Brazil), although some projects in the North Sea use or have used other gases (methane and nitrogen). The reasons for the slow adoption of this CO_2 utilization option may be many, including different reservoir characteristics than onshore; higher recovery rates in many offshore fields than onshore thus lower benefits; fewer wells due to horizontal drilling; expensive modification on platforms. Some recent studies in North Sea countries have explored the possibilities. This review study will summarize recent findings, including the additional monitoring techniques that may be applied offshore. It may position CSLF to encourage members to implement the technology. (NOTE: The CSLF Offshore Storage Task Force is covering some of this topic, but it may warrant a more in-depth review, pending the results of that effort and any recommendations.)

Improved pore space utilization. With the straightforward manner of CO_2 injection, in particular for saline formations, a large portion of available pore space in a geological storage site is bypassed. Utilized storage capacity is typically about two orders of magnitude lower than the pore space resource (the United States Department of Energy (DOE) estimate this efficiency factor to be ~1-4 % of the pore space resource), and the resulting large laterally spread of CO_2 requires costly monitoring relative to the volume stored. Being able to improve pore space utilization may be very beneficial in terms of increased storage capacity, reduced monitoring costs, and increased ability for 'hub' style storage operations. Many research bodies and some operators have investigated options to better utilize the pore space resource. These include: optimizing well(s) configuration and orientation; targeted injection in regions of higher heterogeneity, lower permeability, and/or higher residual trapping potential; plume steering; pressure management; and alternating injection of CO_2 gas and CO_2 dissolved in water. Investigations on these topics is scattered over various research groups and at varying levels of technical maturity. This proposed CSLF study would collate the various published options, and review the effectiveness and readiness of these techniques to improve the pore space utilization. An output from this study would be a (possibly ranked) set of options for stakeholders to develop into their storage projects.

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Additional Task Activities

Advanced Manufacturing Techniques for CCS Technologies. Advanced manufacturing techniques such as 3-D printing have the potential to revolutionize the synthesis and functionality of advanced technologies in many different fields. Objective of this effort is to explore the potential application of advanced manufacturing techniques to CCS technologies.

Dilute stream/Direct Air Capture of CO_2. This effort will explore the current state of the art of technologies that can capture dilute streams of CO_2 (<1% CO_2 concentration) and the economic and technical challenges.

Global Residual Oil Zone (ROZ) Analysis and Potential for combined CO_2 Storage and EOR. Residual oil zones are currently uneconomic but have great potential to store large volumes of CO_2 while producing additional oil. This task force will explore the current status of ROZ resource in the world and its CO_2 storage potential, technical challenges and R&D opportunities.

Study/Report on Environmental Analysis projects throughout the world. Several projects throughout the world have explored the environmental impacts of CO_2 release/CCS (e.g., QICS, CO_2 Field Lab, Montana State University ZERT facility, etc. This study/report would summarize the findings in one concise document and draw conclusions from the work to date and identify opportunities for future work.

Update on non-EOR Utilization Options. In the 2017 timeframe it might be good to re-visit the previous reports and identify progress, status, new ideas. For example, some new ideas for suggested inclusion are compressed air storage as buffer for power generation, and upgrading and treatment of produced brines/enhanced water recovery.

Ship transport. So far pipelines is the dominant way to transport CO_2 for storage. Transport by ships may be an interesting alternative when pipeline is too expensive, e.g. when the need for CO_2 injection is time limited; or when small amounts are transferred to a hub. This study will review and summarize what has been done so far and give recommendations for further work.

Definitions, TRL, scales and other. The work with 2nd and 3rd generation technologies revealed deficiencies and inconsistencies in present definitions and classification of technology maturity for CO_2 capture. Even the NETL definitions are not straightforward to interpret and not well suited for industrial applications. The latter also applies to some extent to metrics for cost performance. Further, apparently, there is no commonly accepted and used definition of what is meant by bench-, lab-, pilot- and demo-scale tests in terms of CO_2 captured, flue gas treated, power delivered or product output. This work will suggest definitions that, when developed in cooperation with IEAGHG and GCCSI, will have a chance of being generally accepted. NOTE: One could expand to include guidelines on how to assess other performances, e.g. energy penalty, although ISO TC265 is looking into this. CSLF probably has a broader participation than ISO and can work faster.

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Industrial CCS. It was previously decided not to have a task force for this but several new reports/studies have become available and industrial CCS is getting more attention. One possibility is for the Technical Group to approach this from the perspective of which 2nd or 3rd generation capture technologies may have applicability to industrial sources. This would be very useful in assessing which have potential and what are the specific challenges. IEAGHG may have done some work in this area but not sure they looked at all technologies or beyond first generation.

Global Scaling of CCS. Produce a simple global model which incorporates by country/region descriptions of current CO_2 emissions by source (e.g., coal power stations, vehicles, etc.). Design the model to allow the user to show the effects on emissions of trends e.g., x%/annum closure of coal, y%/annum increase in gas, z%/annum increase in CCS. Sustain energy use along lines of current trends and track CO_2 storage required is within current storage range estimates. Use the model to explore under which conditions CCS makes its largest/smallest contribution to the prevention of global warming; perhaps using IEA fossil fuel use scenarios and emission reduction scenarios as the reference guide to assessing the role of CCS as a start.

Compact CCS. New technologies such as those using supercritical CO_2 are being developed and offer small plant footprints, at least for power production and capture. A study which evaluates how "small" various CCS plants could be made could inform us about potential operation in areas sensitive to plant size (height or footprint), or the potential for offshore operation, with savings on long gas pipelines.

Capturing CO_2 from mobile application. This effort is to evaluate a CO_2 capture technology on-board a vehicle that mitigates CO_2 emissions from the transportation system. It is done through the separation of CO_2 after the combustion process using post-combustion CO_2 capture technology.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2015-08
20 October 2015

POLICY GROUP

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

Background

At the November 2013 CSLF Ministerial Meeting in Washington D.C., the Exploratory Committee of the CSLF 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. "

Accordingly, 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 was formed to:

- Identify emerging 2nd and 3rd generation emerging technologies for CO_2 capture and testing facilities;
- Assess associated enabling mechanisms at a high level; and
- Propose potential areas of follow-up for the CSLF to facilitate the acceleration of 2nd and 3rd generation carbon capture technologies.

The following is a final draft of the Task Force report.

Action Requested

The Technical Group is requested to review the Task Force report.

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Carbon Sequestration Leadership Forum

www.cslforum.org

Final Draft
15 October 2015

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 in the order of 100 tonnes per day and more.

The study is based on a literature and web review of the status of emerging (2nd and 3rd generation) CO_2 capture technologies and existing test facilities. It was performed jointly by the CSLF Policy and Technical Groups. Neither the inventory of emerging technologies nor of test facilities can be regarded as complete.

Around 30 groups of 2nd and 3rd generation (emerging) CO_2 capture technologies have been identified. Most are 3rd generation, i.e. Technology Readiness Level (TRL) 1 – 3(4) and must be classified as tested at laboratory or bench scale only. A minority is classified as 2nd generation, i.e. TRL 4(5) – 6. The results are summarized in Table 1 below.

The potential for cost end energy consumption reductions vary from very small to significant in the above table. However, it is important to note that the numbers are based on a literature survey and may not be derived in a consistent manner. Furthermore, the technologies are at different levels of maturity, which will influence the uncertainties of the estimates. Factors that contribute to the uncertainties include:

- Comparison to different baselines (old, new, unfavourable, etc. in addition to different assumptions and battery limits)
- Cost unit (e.g. cost of electricity (COE), levelised cost of electricity (LCOE), cost per tonne CO_2 captured or abated
- First of a kind (FOAK) or nth of a kind (NOAK)
- Basically unfamiliar production methods and materials
- Reporting in efficiency changes (% relative some baseline) or energy requirements (GJ/tonne CO_2)
- Electricity vs. thermal energy
- Work vs. thermal energy
- Limited information and testing of emerging technologies.

It is important to be conscious of these uncertainties when choosing technologies for further development and testing.

The study has identified 11 test facilities for CO_2 capture technologies that are or will be independent of technology providers and that may be used to speed up the development of emerging capture technologies. Only two of these are sufficiently large to allow the next step in the technology development to be full scale. The other must be classified as small scale testing capabilities, i.e. < 10 000 tonnes CO_2/year or the equivalent of 2 MW coal fired power. These are often run on simulated flue gas. Testing at these smaller facilities will require at least one intermediate step before going to full scale. The majority of the identified test facilities are designed for post-combustion capture of CO_2.

Table 1. 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. Also note that cost reduction usually refer to reduction of Levelized Cost of Electricity (LCOE) but for some (high ones) it may only be for the capture component.
?=Uncertain estimates that are not quoted

Table 1A. Post-combustion capture technologies

Technology	Generation/ TRL	Potential for energy savings	Potential for cost reduction	Applications
Precipitating solvents	2nd-3rd/4-6	10-20% rel. MEA (2.3-3.6 GJ/t CO_2)	5-10%	Power, steel, cement
Two-phase liquid system	2nd-3rd/4-5	2.0-2.3 GJ/t CO_2	5-10%	Power, steel, cement
Enzymes	3rd/1-2(3)	30-35% rel. MEA (?)	5-10	Power, steel, cement
Ionic fluids	2nd-(3rd)/1 – 4	15 -20 % rel. MEA	?	Power, steel, cement
Encapsulated solvents	3rd/1-2	?	?	Power, cement
Electrochemical solvents	3rd/1-2	Uncertain	Uncertain, may be none	Power, cement, steel, aluminum
Calcium looping system	2nd/5-6	Coal: Efficiency penalties 5-10% Gas: no benefits	May be significant	Power, cement
Other looping systems	3rd/1-2	?	?	Power, steel, cement
Vacuum Pressure Swing (VPS)	3rd/2-3	Uncertain, could be good	May be not	Power, cement
Temperature swing (TS)	3rd/1-2	Uncertain, appears limited	?	Power, cement
Polymeric membranes	2nd/5-6	Fuel consumption: 50% down rel. MEA?	30%	Power, cement, steel
Polymeric w/cryogenic	2nd/2-6	Better than above	30%	Power, cement, steel
Cryogenic (low temp)	2nd-3rd/3-5	Competitive MEA	Moderate ?	Power
Supersonic	3rd/1-2	?	?	Power
Hydrates	**3rd/1-3**	**?**	**?**	**Power**
Algae	3rd/1-3	?	?	Power and most other industries
CO_2-enriched flue gas	2nd/5-6	?	?	Power
Pressurized post-combustion	2nd-3rd/2-5	?	?	Power

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Table 1B Pre-combustion capture technologies

Technology	Generation/TRL	Potential for energy savings	Potential for cost reduction	Applications
Sorption Enhanced Water Gas Shift (SEWGS)	2nd/4-5	Efficiency gain 3-4 %-points	May be up to 30%	Power, refinery, H_2 production
Sorption Enhanced Steam-Methane reforming (SE-SMR)	3rd/1-2	Appears limited in NGCC	?	Power, refinery, H_2 production
Metal and composite membranes	2nd-3rd/3-5	Efficiency gain 3 %-points	May be up to 25-30% (?)	Power, refinery, H_2 production
Ceramic membranes	2nd-3rd/2-4	As above?	May be up to 25% (?)	Power, refinery, H_2 production
Cryogenic (low temperature)	3rd/1-3	Efficiency gain 3-4 %-points; 1 GJ/t CO_2	30 – 50% (last w/ recycle of CO_2)	Power, refinery, H_2 production
Concepts with fuel cells	2nd-3rd/3-6	Efficiency gain up to 30 %-points rel. IGCC and gas w/MEA	> 70%	Coal and biomass power, refinery, H_2 production

Table 1C Oxy-combustion capture technologies

Technology	Generation/TRL	Potential for energy savings	Potential for cost reduction	Applications
Chemical looping combustion	3rd/2-3	Efficiency gain 2-4 %-points (?)	Large	Coal power
Oxygen transporting membranes (OTM) power cycle	3rd/2-3	Efficiency gain 5 %-points over NCCC w/MEA(?)	?	Power
Pressurized oxy-combustion	3rd/2-4	~35- 40% - efficiency	reduction 22 – 32+%, on power, depending on cycle	Coal and biomass power

There also several test or demonstration facilities for CO_2 capture technologies that are owned by technology providers to test specific proprietary technologies. These are in general not available for testing of other technologies. Some of these facilities are briefly described in the report.

The study revealed that the literature uses a range of definitions for technology maturity and test scales and sometimes inconsistent use of terms. For example, although it is difficult to avoid a gliding scale between the terms “pilot” and “demonstration” size facilities, a difference in terms of captured CO2 has been found to vary with almost 3 orders of magnitude and at least one order in terms of power.

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Recommendations for Follow-Up by CSLF

Many technologies are developed by universities or small R&D companies that do not have the resources, financial and competence, to take the development further without support by others and access to one level larger test facilities. To progress the 2nd and 3rd generation CO_2 capture technologies further in a cost efficient manner CSLF should consider the following:

- Implement mechanisms that allow developers of emerging technologies and operators of test facilities to cooperate in mutual beneficial and cost effective ways, e.g. help establishing bi- and/or multi-lateral agreements and funding mechanisms that allow emerging technologies to be tested at another nation's facilities. The International Test Centre Network (ITCN) and the European network ECCSEL initiatives are examples of how governments cooperate to increase testing capacities
- Promote cooperation between facilities with different capabilities, both below and above 2MW or (10^4 tons CO_2/year, ~ 30 tons CO_2/day). This would increase the range of test opportunities and facilitate and accelerate knowledge sharing and exchange of experiences among member countries and between two or more test facilities
- Based on the successful model of the ITCN and ECCSEL, CSLF should encourage and facilitate enhancing the networks to cover additional regions, sectors, and levels of scale. This would help to lay the ground to accelerate the development and testing of technologies in additional environments and facility configurations / conditions. As well, with increased membership, costs can be spread across a larger number of participants
- Enhance opportunities for researchers and developers to participate in extended visits and staff exchanges to other demonstration projects and test centres (6 months or more) as well as training opportunities, much along the lines of the European initiative ECCSEL. This item should be coordinated with the re-established CSLF Academic Community Task Force.
- Contribute to derivation of a consistent terminology for new CO_2 capture technologies, maturity (2nd and 3rd generation vs. emerging or transformational; consistent use of Technology readiness level, TRL) and for different testing scales (bench, lab, pilot, demonstration)
- Contribute to derivation of consistent performance indicators, e.g. common methods for cost and energy consumption.

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], as well as presentations at the 2014 NETL CO2 Capture Technology Meeting, Pittsburgh, PA, USA, July 29 – August 1, 2014,[7] and the 2014 Transformational Carbon Capture Technology Workshop, Arlington, VA, USA, September 23[8], 2014. References to these documents or presentations at the conferences 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.

[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.netl.doe.gov/events/conference-proceedings/2014/2014-netl-co2-capture-technology-meeting

[8] http://www.netl.doe.gov/research/coal/carbon-capture/workshop-2014

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)[9], CSLF (2013a, 2013b[10]), US DOE/NETL (2013), ZEP (2013), GCCSI (2014) and 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

[9] http://www.apgtf-uk.com/index.php/publications/publications-2011
[10] http://www.cslforum.org/publications/documents/CSLF_Technology_Roadmap_2013.pdf

	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

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 8	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.
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 3	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.
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. The former indicates a factor of $O(10^3)$, which is too large to be meaningful.

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 Potential for improvements

A summary of emerging technologies would be incomplete without assessments of the potential for reductions of cost and energy consumption compared to some selected baselines. Choice of baseline is an important issue and ideally, one would prefer a common baseline. However, this is not always possible and the choice varies between technology developers. Thus, fair and direct comparisons of potentials for improvements may not always be possible. Numbers presented here should be used with extreme care.

Factors that may contribute to different estimates include:

- **Cost**
  - Comparison to different baselines (old, new, unfavourable etc in addition to different assumptions and battery limits)
  - Cost unit (e.g., cost of electricity (COE), levelised cost of electricity (LCOE), cost per tonne CO_2 captured or abated
  - First of a kind (FOAK) or nth of a kind (NOAK)
  - Basically unfamiliar production methods and materials.

- **Energy:**
  - Comparison to different baselines (old, new, unfavourable etc in addition to different assumptions and battery limits)
  - Reporting in efficiency changes (% vs. some baseline) or energy requirements (GJ/tonne CO_2)
  - Electricity vs. thermal energy
  - Work vs. thermal energy
  - Limited information and testing of emerging technologies.

Here we base cost reduction numbers on IEAGHG (2015), where the LCOE was estimated based on numbers from technology vendors. Baselines were

– Post-combustion: Econamine applied to supercritical steam, coal fired power plant
– Pre-combustion: Integrated Gasification Combined Cycle (IGCC) with Selexol capture
– Oxy-combustion: As post-combustion.

However, it appears sometime uncertain if LCOE id based on the whole process or only based on the new capture component.

Improvements in energy consumption are based IEAGHG (2015) and SINTEF (2013). The baselines for the IEAGHG(2015) numbers are as for cost reductions. The reporting of energy reduction potential in the SINTEF (2013) report includes qualitative assessments, aboslute energy consumption and references to MEA based post-combustion capture.

Numbers for potential for reduction of energy consumption given in the present report are subjective syntheses and summaries of numbers found in the referenced documents.

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

Several retrofit 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.

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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.

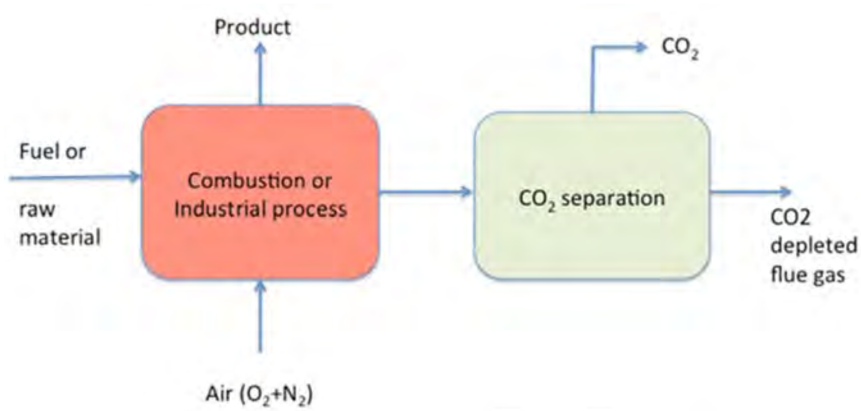

Figure 1. Schematic illustration of the post-combustion process

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 that have tested their commercial solvents at scale of several MW and above, include

- Aker Solutions (earlier Aker Clean Carbon)
- Alstom
- Fluor

- Linde-BASF
- Mitsubishi Hitachi
- Toshiba

The solvents usually involve amines based solutions. Alstom also has a technology based on chilled ammonia. They all continue R&D to improve the solvents.

Others that have announced their intention to test proprietary solvents at the CO2 Technology Centre Mongstad (TCM) are

- Carbon Clean Solutions PVT. LTC (CCS), an India based company that has developed a solvent in which amine-based compounds are combined with salts, the CDRMax solvent. The proprietary solvent was tested at Solvay Chemicals' 7700 tons per annum CO_2 capture plant at Vishnu Barium, India in 2012.
- General Electric Global Research has developed a solvent based on amino silicone compounds that at various temperatures to capture and release carbon. GE researchers are preparing (fall 2015) a demonstration of it CO2 Capture solution in 0.5MW power system the US National Carbon Capture Center (NCCC).

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 (e.g. K_2CO_3) 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 4-6 (Lab scale testing to small pilot-scale with real flue gas; depending on solvent)
- **Potential for improvements:**
    - Energy savings: 10 – 20% (energy consumption 2.3 – 3.6 GJ/t CO_2)
    - Reduction of LCOE: 5 – 10%
- **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. Solid liquid separation is an additional process step and needs to be optimised

- **Some players**: Shell Global Solutions, Alstom, CO2CRC, SINTEF/NTNU, TNO, GE Global Research/University of Pittsburgh
- **Pathway to technology qualification**: On-site testing with real flue gas at e.g. a few tens 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, other small industries.

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)
- **Potential for improvements:**
  - Energy savings: Energy consumption 2.0 – 2.3 GJ/t CO_2
  - Reduction of LCOE: 5 – 10%
- **Challenges:** Tailoring and characterizing the system to minimize the energy requirement; firmer validation
- **Some players**: IFPEN with partners in the Octavius Project, 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)
- **Potential for improvements:**
  - Energy savings: 30 – 35 %
  - Reduction of LCOE: 5 – 10%
- **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); finding the optimal enzyme concentration
- **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.

CO_2 Binding Organic Liquids (BOLs) are switchable ionic liquids that convert a non-polar liquid to a polar ionic liquid with CO_2 as the chemical trigger. If coupled with the newly discovered polarity-swing-assisted regeneration (PSAR) process CO_2BOLs are estimated to provide more than 42 percent energy savings over aqueous alkanolamine systems due to significantly lower temperatures and energy requirements for CO_2 separation relative to conventional technology, making appreciable cost savings possible.

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
- **Potential for improvements:**
    - Energy savings: 15 – 20%
    - Reduction of LCOE: Uncertain
- **Challenges:** Optimization of chemical/physical properties to overcome high viscosity problems, lowering the thermal energy requirements for CO_2 desorption and reduce costs of IL
- **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, Batelle Pacific Northwest Laboratories, University of Melbourne 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)
- **Potential for improvements**:
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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 tens 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 Metal Organic Frameworks

MOFs is a class of crystalline porous materials that consists of organic ligand molecules that are able to bind metal ions that hold some promise to improve cost and performance of CO_2 capture technologies based on sorbents. Their advantages include

- High tuneability with respect to surface chemistry and pore size, i.e. a very large number can be synthesized from different metal ions and different linkers
- Very high surface area, up to 5000 m^2/g
- Thermal stability
- Potentially high concentration of adsorption sites

Challenges connected to MOFs include

- Synthesising and fabricating novel MOF materials with exceptional CO_2 separation capacities at affordable cost
- Developing MOF materials with catalytic abilities for CO_2 conversion into usable products
- Scale-up and fabrication of membrane-based devices for integration of MOFs into industrial platforms
- Modelling, prediction and advanced characterisation of these new materials.

Many academic and research institutions work on MOFs. Due to many combinations of different metal ions and different linkers, they are not described further.

4.2.2 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 ºC and in the calciner 850 – 1000 ºC. Advantages of the calcium looping process are that the output from the calciner is 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 but to some extent also 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 loses 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)
- **Potential for improvements:**
  - Energy savings: 5 -10 % for coal; small for gas
  - Reduction of LCOE: Uncertain, may be significant
- **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, may require studies on more advanced sorbents but the additional cost of advanced sorbents may not be justified by the improved performance. 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, Australia 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.

4.2.3 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, K_2CO_3 and Na_2CO_3 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_e with K_2CO_3 based sorbent on slip-stream of KOSPO's Hadong coal fired power plant, Korea
- **Potential for improvements:**
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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 and and KIER in 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.

4.2.4 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. One hypothesis is that the energy requirement will 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. The costs of MOFs are a concern.

- **Maturity:** 3rd generation; TRL 2 - 5 (Lab Scale testing with real flue gas)
- **Potential for improvements:**
    - Energy savings: Uncertain
    - Reduction of LCOE: Uncertain
- **Key Challenges**: Need to investigate the impact of SO_2 and NO_X and achieving high recovery of CO_2; as well as 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, CO2CRC, 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 tens of tonnes of CO_2/hour.. Further research on adsorption materials and optimization of operating cycles 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, other small industries.

4.2.5 Temperature swing adsorption (TSA)

In a TSA process, CO_2 is adsorbed on a high surface area material at low temperature (40-60ºC) 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 step is usually heat in the 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 80-150ºC) 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)
- **Potential for improvements**:
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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 Industries, Japan, Adsorption Research Inc (SRI) and Inventys, adsorbent producers Grace, UOP, and Zeolyst, Georigia Institute of Technology, CO2CRC/The University of Melbourne, 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 ºC (for regeneration). The KCC system may use steam at 60 ºC
- **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 Polymeric and hybrid 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)
- **Potential for improvements**:
  - Energy savings: May be up to 50%
  - Reduction of LCOE: Up to 30%
- **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, CO2CRC
- **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 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, other small industries.

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 ºC to – 45 ºC), as membrane selectivity and permeance 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).
- **Potential for improvements:**
  - Energy savings: 50% or perhaps more
  - Reduction of LCOE: Up to 30%
- **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, Monash University.
  - 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 ºC must be added
- **Environmental impact**: None is expected as there are no chemicals involved
- **Applications**: Power industry, cement industry, steel industry.

4.3.3 Molten Carbonate Fuel Cells

Here we choose to classify Molten Carbonate Fuel Cells (MCFCs) as membranes, in lack of a better place. MCFCs use carbonate salt suspended in a porous ceramic matrix as the electrolyte. Salts commonly used include lithium carbonate, potassium carbonate and sodium carbonate. They operate at high temperature, around 650ºC and there are several advantages associated with this. MCFCs can be used to capture CO_2. When flue gas is supplied to the cathode side of the fuel cell, rather an air, the CO_2 in the exhaust gas is transferred to the anode side if the cell. There it is concentrated, separate and liquefied for transport.

One advantage of MCFCs is that produce power while capturing the CO_2.

- **Maturity**: 3rd generation/TRL 3-4 (Small scale lab)
- **Potential for improvements:**
  - Energy savings: Could results in efficiency increase
  - Cost: May come down to below $0.05/kWh at 90% capture
- **Key challenges**: Obtain better cost end efficiency estimates; sulphur in flue gas may be affect performance and operational costs. Disadvantages associated with MCFC units arise from using a liquid electrolyte rather than a solid and the requirement to inject carbon dioxide at the cathode as carbonate ions are consumed in reactions occurring at the anode. There have also been some issues with high temperature corrosion and the corrosive nature of the electrolyte but these can now be controlled to achieve a practical lifetime.
- **Some players**: FuelCell Energy. Others may also be around
- **Pathway to technology qualification**: First step is tests at larger scale
- **Infrastructure required**:
- **Environmental impact**: Probably limited
- **Applications**: Power production, cement, steel.

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. However, using hybrid technologies, e.g., along with membrane and/or adsorbent to increase the CO_2 concentration in the feed gas looks a better possibility as explained above (4.3.2).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)
- **Potential for improvements**:
  - Energy savings: Competitive with MEA
  - Reduction of LCOE: Uncertain
- **Key Challenges**: Pilot testing is needed to determine the specific capture work and efficiency; develop hybrid technology approach
- **Some Players**: GE, Shell Global Solutions, Alstom, Eindhoven University of Technology, MINES ParisTech, CO2CRC/Curtin University, Brigham Young University
- **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)
- **Potential for improvements:**
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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. However, this technology is at an early stage of development and an indication of the modesty of energy penalties would be welcome.

- **Maturity**: 3rd generation (Concept studies to bench-scale)
- **Potential for improvements:**
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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, Curtin University
- **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 sufficient 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 planktonic 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
- **Potential for improvements**:
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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), understanding impacts of trace contaminants (e.g. heavy metals) is required

- **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, Natural Live Plankton (NLP, www.nlp21.co.kr, Korea)
- **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)
- **Potential for improvements:**
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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 100ºC 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
- **Potential for improvements**:
  - Energy savings: Uncertain
  - Reduction of LCOE: Uncertain
- **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. Materials of construction will have to compatibility with potassium carbonate
- **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.

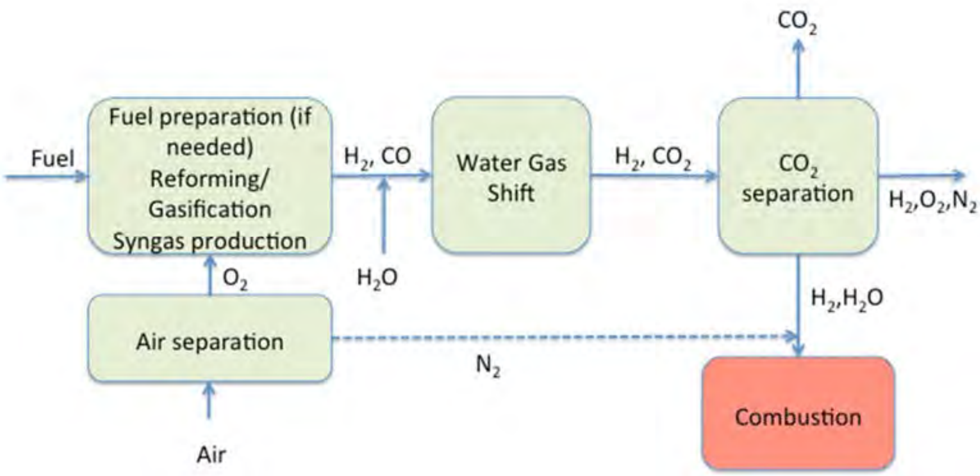

Figure 2. Schematic illustration of the pre-combustion process

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™, 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™, 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 ongoing research and development to improve existing 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

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Innovative Technology for the Earth (RITE), who cooperate on the developments of a capture process with a chemical solvent called RH-x, which RITE developed for high-pressure conditions. RH-x is suitable for pre-combustion capture because of its capability of CO2 regeneration at a high pressure which inlet gases have. This high-pressure regeneration will lead to lower energy consumption in CO2 compression for transportation to a storage site and consequently to cost reduction in CCS operation.

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 inert gases) 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)
- **Potential for improvements:**
  - Energy savings: Efficiency gain 3 – 4 %-points
  - Reduction of LCOE: Up to 30%
- **Key challenges**: Prove or long term stability of sorbents with high volumetric cycling capacity, develop alternative sorbent system operation, providing steady stream of H2 for use
- **Some players**: ECN (Netherlands), TDA Research, URS Group, Air Products, Korea Electric Power Corporation Research Institute (KEPCO RI) and Korea Institute Of Energy Research (KIER)
- **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. The CO_2 adsorption is exothermic, but the calciner process is highly endothermic, i.e. heat must be supplied, typically through direct combustion of oxygen and natural gas in the calciner. The resukt is an overall process that 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)
- **Potential for improvements:**
    - Energy savings: Uncertain
    - Reduction of LCOE: Uncertain
- **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 (i.e., H_2 permselective membranes). 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. There are, however, a number of membranes made of other materials (e.g. polymers), which are in general at the same stage of development as metallic and ceramic membranes. Outstanding developments of highly CO2 permselective polymeric membranes include poly(amidoamine) dendrimer / poly(vinyl alcohol) hybrid membranes advanced in Japan.

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)
- **Potential for improvements**:
    - Energy savings: Efficiency gain 3 %-points
    - Reduction of LCOE: up to 25 – 30%
- **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 adequate 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 operate at higher temperature than Pd membranes.

- **Maturity**: 2nd - 3rd generation; TRL 2 - 4 (Lab scale to vey small pilot testing)
- **Potential for improvements**:
    - Energy savings: Efficiency gain 3 %-points
    - Reduction of LCOE: up to 25 %
- **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; CO2CRC in cooperation with UQ ;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. H_2S, 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 – 50ºC. 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 -150ºC 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)
- Potential for improvements:
- Energy savings: Efficiency gain 3 – 4 %-points
- Reduction of LCOE: Up to 30 - 50% (the latter with recycle of CO_2)
- **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, CO2CRC in cooperation with Curtin University
- **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.

5.5 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:** 2^{nd} to 3^{rd} generation; TRL 3 – 6 (Concept study, small-scale sub-system validation in relevant environments)
- **Potential for improvements:**
    - o Energy savings: Efficiency gain up to 30 %-points relative MEA and IGCC w/capture (assumes improved fuel cell, up to 20% %-points with baseline fuel cell)
    - o Reduction of LCOE: 25 -30 % with baseline fuel cell; up to 45% with improved fuel cell)
- **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 could be 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:** 2^{nd} -3^{rd} generation (Pilot testing)
- **Potential for improvements:**
    - o Energy savings: May achieve > 70% when heat and H2 production and utilization are included
    - o Reduction of LCOE: Uncertain
- **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.

5.6 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 has 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.

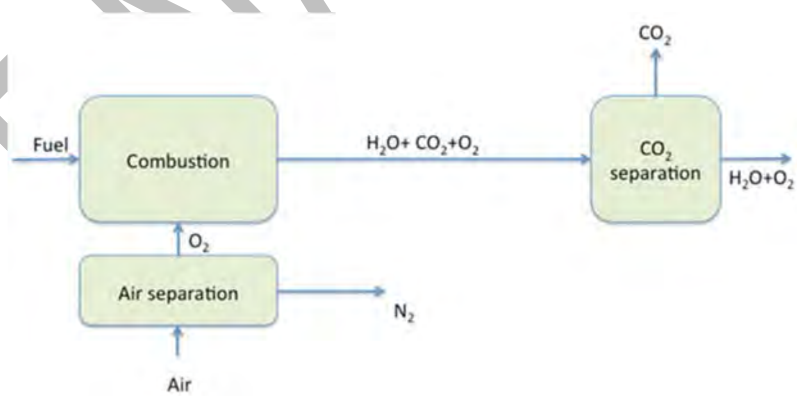

Figure 3. Schematic illustration of the oxy-combustion process

The CO_2 separation in the oxy-fuel process is straight forward, and the challenges lie within air separation and combustion. In this case the development may be along 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).
- **Potential for improvements:**
  - Energy savings: Efficiency gain 2 – 4 %-points
  - Reduction of LCOE: May be large but uncertain
- **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, Monash University, University of Newcastle, CanmetENERGY, University of Ottawa, University of Calgary, University of British Columbia, Alberta Innovates – Tech Futures, University of Kentucky
- **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 and limestone) are required. Thers is an option 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.
Current technology focus is on systems operating at atmospheric pressure, but higher efficiency is possible at high pressure. More development work is required to develop the high pressure technology variant.

- **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 Pressurized Oxy-Combustion

Description

Pressurization of the oxy-combustion process results in increased cycle efficiency through recovery of the latent heat of water vapour at a sufficiently high pressure to effectively utilize the heat in the power cycle. Capital cost is reduced due to reduction in equipment size and increased heat transfer rates. Flue gas processing is simplified since various impurities such as SO_X, NO_X, O_2 and H_2O are removed much more easily at elevated pressure allowing additional reductions in capital cost.

- **Maturity:** 2nd to 3rd generation; TRL 2 -4 (Pilot scale testing up to 5 MW_{th}).
- **Potential for improvements:**
  - Energy savings: 6+ percentage point improvement
  - Reduction of LCOE: 32% compared to pulverized coal with 1st gen post combustion capture
- **Key Challenges**: SOx management to mitigate corrosion issues, very compact heat transfer equipment at high temperature, for very high pressure systems gaseous reactants and flue gas are non-ideal (i.e. near supercritical point) which challenges CFD modelling software used for scale-up, flue gas chemistry at high pressure.
- **Some Players**: Alstom, GTI, Linde, CanmetENERGY, University of Ottawa, Czestochowa University of Technology, ITEA, Media & Process Technology, Florida International University, SmartBurn, Reaction Engineering International, University of Utah, Praxair, Jupiter Oxygen Corporation, Washington University.
- **Recommended pathway for technology qualification.** There are a variety of competing pressurized oxy-combustion technologies which are ready for qualification at ~ 1MW_{th}. The different technologies have various pro's and con's which may make them most suitable for a given application and fuel – it is still too early to decide which technologies will be commercialized. Some of these technologies should be selected for demonstration at the 50 to 100 MW_{th} scale by about 2020. Many of the technologies will require similar flue gas processing which differs from atmospheric pressure requirements in many respects, so a sustained effort in developing new flue gas processing methods could be complementary to the pressurized oxy-combustion technologies. Many of the technologies use pulverized fuel, so advances in solids pressurization technology, such as are under development for gasification, would be beneficial.
- **Infrastructure required**
  - Fuel supply
  - Oxygen supply

- Pressurized flue gas processing
- **Environmental impact:** None expected.
- **Applications:** Power industry and industries using steam, combined heat and power applications.

6.3 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)
- **Potential for improvements:**
  - Energy savings: Efficiency gain more than 5 %-points over NGCC w/MEA
  - Reduction of LCOE: Uncertain
- **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.

6.4 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.

6.4.1 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.

6.4.2 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[11]; Higginbotham et al, 2011[12]). This is expected to have significant impact on the energy efficiency of oxygen production (see IEAGHG 2014 for more). However, the trade-off is oxygen purity.

6.4.3 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 has been assessed and pilot tested at 0.7t/day.

6.4.4 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.

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

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

- **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.

6.4.5 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 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
- **Applications:** Power industry.

6.4.6 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.

6.4.7 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 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 gas 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 detail in open literature have recently received funding. Below follow brief descriptions organized by country. CSLF member states were asked to provide information on these but the response was very low. Thus only concepts from one country have been included for this version.

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

This chapter will briefly summarize the capabilities of some test facilities for CO_2 capture technologies. We distinguish between two kinds of test facilities as follows:

- Independent test facilities are plants that ideally are independent of technology vendors and developers and of are capable of and willing to test technologies on a neutral basis. Requirement on size is that they are larger than bench and laboratory scale. Ideally, they will be connected to a power or industrial plant and be able to test on real flue gas but this is required
- Dependent facilities are built to test one specific capture technology and are closely linked to one technology provider. Their size may vary from a few hundred kW up some tens of MW.

The descriptions below are not complete. CSLF member states were asked to provide input to this chapter but none was received and the chapter is based on general knowledge and web searches.

We apologize for forgotten or overlooked facilities.

8.1 Independent Test Facilities

8.1.1 The International CCS Test Centre Network (ITCN)

ITCN is a network of five test facilities that have the ability to test some kind or another of capture technologies at scales ranging from a few tens of tonnes CO_2 per year up to more than 50 000 tonnes CO_2 per year. With one exception they are committed to test technologies from more than one vendor. Brief descriptions of the member facilities follow below.

National Carbon Capture Center, USA:

- Operated by Southern Company
- Cost-effective, flexible test bed to demonstrate and develop pre- and pos-tcombustion CO_2 capture technology in an industrial setting with coal derived gas
- Post-combustion:
  - Multiple test bays available up to a flue gas capacity equivalent of 4.3 MW_e (flue gas stream ~ 17 000 kg/hr)
  - CO_2 concentration in flue gas 14 %, may be diluted with air to 3 %
- Pre-combustion:
  - 6.3 MW_e Trig gasifier
  - Air and O2 fired syngas
  - Syngas stream 750 kg/hr
- Infrastructure: Water and electricity available
- Partners – US DOE, EPRI, Duke, AEP, Luminant, Arch Coal and Cloud Peak Coal.

CO2 Technology Centre Mongstad, Norway:

- Two sites for testing post-combustion technologies: amine and chilled ammonia
- One site available for other technologies
- Two flue gas sources, refinery and Combined heat and power (CHP)
- Refinery FCC flue gas: CO_2 concentration 12 – 14 %; flue gas stream 22 – 50000 Sm^3/hr;100 CO_2 capacity 80 000 per year (equivalent to ~ 10 -12 MW coal)
- CHP gas turbine flue gas: CO_2 concentration 3.5 - 9 %; flue gas stream 28 – 56000 Sm^3/hr; CO_2 capacity 20 000 per year (equivalent to 7 - 8 MW gas)

- State of the art on-site laboratory, workshop and central control rooms
- Infrastructure: Water and electricity available
- Owned by the Norwegian state (represented by Gassnova), Statoil, Shell and Sasol.

Shand, Canada:

- Flue gas from 300 MW coal-fired (lignite) unit at SaskPower's Shand Power Station
- Amine based post-combustion capture (Mitsubishi Hitachi Power Systems) with capacity for 45 000 tonnes of CO_2 per year (equivalent to 7 -8 MW coal)
- Technical support including on-site and central laboratory and engineering staff with commercial CO_2 capture experience
- Infrastructure: Water and electricity available
- Available for other tests in 2017, also other capturing technologies
- Owned by SaskPower.

Wilhelmshaven, Germany:
Not really independent but included here due to its membership in ICTN

- CO_2 capture process based on Fluor Econamine FG plus Technology
- Treating real coal-fired power plant flue gas
  - Capacity of 25 000 tonnes CO2 per year, equivalent to 4 -5 MW coal
  - Slip stream 16 000 Nm^3/year, CO_2 concentration 13 %
- Integrated into power plant operation control
- Sophisticated on-site lab
- Infrastructure: Water and electricity available
- Owned by E.On.

Pilot Advanced Capture Technology, UK:

- Treating flue gas from coal, gas and biomass stand alone units (not connevted to plant)
- Two 330kW Gas Turbines; One 250kW air/oxyfuel combustion plant; one 1.5 MW_{th} gas turbine burner
- Both integrated with a 1 tonne of CO2 per day Carbon Capture Plant, and a gas mixing facility with trace gas injection capability
- Mobile carbon capture lab unit
- Analytical labs
- Infrastructure: Water, electricity, gas mixing
- Partners Universities of Cranfield, Edinburgh, Imperial College, London, Leeds, Nottingham and Sheffield, part of the UK Carbon Capture and Storage Research Centre.

8.1.2 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.

Some ECCSEL capture test facilities are:

Tiller, Norway

- Post-combustion: Flue gas from propane burner
  - Power equivalent to 140 kW gas
  - CO_2 concentration 3 – 20 %
  - Infrastructure: Absorption tower (20cm inner diameter and 19.5 meter height) stripper column 13.6 meter, electrically heated re-boiler 60 kW
  - Monitoring: Accurate measurement of energy requirements, emission measurements, solvent degradation properties and other process performance parameters.
  - The process is automatically operated
- Separate 150 kW Chemical Looping rig
- Owner: SINTEF.

es.CO2, Cubillos del Sil, Spain

- Oxy-combustion
- Pulverized coal: 20 MWth; Circulating Fluidized bed: 30 MWth; Biomass: 3 MWth
- Infrastructure:
- Flue Gas Cleaning System
- Recycled Gas Preparation System
- CO_2 Compression and Purification Unit (CPU)
- CO_2 Transport Experimental Facilities.
- Fully Equipped Laboratory
- Owner CIUDEN.

University of Stuttgart, Germany

- Post-combustion
- Calcium Looping rig 200 kW.

THAHRA, the Netherlands (TNO's High-Pressure Absorption Hybrid Regeneration Apparatus)

- Owner: TNO.

ETH Z, Switzerland

- Post-combustion, direct mineralization.

8.1.3 Other independent test facilities

Australia

- CSIRO Loy Yang Pilot Plant
  - Post-combustion
    - Flue gas from coal fired power plant

- MEA based solvents
- Capacity 1000 tons CO_2/year.

Canada

- CanmetEnergy: 0.3 MW_{th} vertical combustor facility, oxy-combustion, slip streams for pre- and post-combustion possible. 1 MW_{th} under construction
- Husky Energy Pikes Peak: Post-combustion, flue gas from 14 MW steam generator, capacity 15 tons CO_2/day, hope to expand to 150 tons CO_2/day. Under construction.

Italy

- CCS Brindisi CO_2 Capture Pilot Plant (not in operation as of September 2015)
- Post-combustion capture with amine
- Slip stream form 2640 MW coal fired power station
- Capture rate 8000 t CO_2/year
- Large range to change the composition of flue gas
- High flexibility in fact of solvent flow rate; flue gas flow rate, DCS control system, solvent inventory
- Owned by ENEL.

Poland

- Tauron in cooperation with Institute of Chemical Processing of Coal (ICPW)
- The mobile CO_2 capture solvents and VPSA mobile unit
    - Captures 1,2 t CO_2/day from real flue gas
    - Column diameter: 0.3m
    - Absorber height: 14.0m
    - Desorber height: 15.0m
    - Tested at Lagsza and Jaworzno power plants.

USA

- Environmental and Energy Research Center (EERC), Univ. of North Dakota, USA:
    - Three systems:
        - One oxy-fired that generates 140 scfm of flue gas with 85% CO_2
        - Two post-combustion systems: solvent absorber and solid sorbent
        - Flue gas from a combustion test facility equivalent of 0.15 – 0.20 MW that runs on coal or biomass.

In planning

- UK-China (Guangdong) Carbon Capture, Utilisation and Storage (CCUS) CentreUp to 200 t CO_2/day post- combustion facility in planning
- University of Wyoming, plans 1 MW+ postcombustion test facilty for coal based power
- Carbon Management Canada Research Institutes, with NORAM Engineering and BC Research to develop a new Technology Commercialization and Innovation Centre for development, scale-up and pilot testing for CO2 Capture and Conversion technologies, capture facility 1 t CO_2/day or 0.1 MW.

8.2 Dependent test facilities

Information marked "MIT" is taken from https://sequestration.mit.edu/tools/projects/index_pilots.html. This web-site includes active as well as terminated projects, although some that are listed have now moved into the terminated category, such as the above mentined Brindisi and La Havre.

China

- Huaneng (Dr. Xu Shisen (2014) CCUS Progress in China. Presentation at GHGT-12, Austin, Texas, USA, October 2014)
    - 3000 tons CO_2/year post-combustion Capture In Bejing (
    - Verification Plant for post-combustion capture from coal and natural gas tons 1000 CO_2/year (reference as above)
    - 10000 CO_2/year precombustion facility Palladium membrane H_2/CO_2 separation system.

- Shidongkou Carbon Dioxide Capture and Storage Project (MIT)
    - Company/Alliance: Huaneng Power Group
    - Location: Shanghai China
    - Feedstock: Coal
    - Size: Part of 600 MW reactor: 0.1 Mt/yr (approximately 4% of a single unit's output)
    - Capture Technology: Post-combustion using an amine mix (Huaneng is secretive about its capture technology).

France (MIT)

- Located at EDF coal power plant at Le Havre (not in operation as of September 2015)
- Post-combustion on flue gas from pulverized bituminous coal
- Alstom Advanced Amine Process
- CO_2 capacity 7500 tonnes per year.

Japan

- Kawasaki Heavy Industries, Ltd. (http://injapan.no/energy2015-day2/)
    - Fixed-bed (10 t CO_2/day) and moving-bed (3 t CO_2/day) systems with own adsorbent
- Mitsubishi Heavy Industries (http://injapan.no/energy2015-day2/)
    - Several test, pilot and demonstration scale projects based on own amine technology
- Tomakomai (MIT)
    - Company/Alliance: Japanese Government JCCS
    - Location: Tomakomai, Hokkaido Islands, Japan
    - Feedstock: Hydrogen production unit
    - Size: 0.1 Mt/yr
    - Capture Technology: Activated amine process
- Toshiba (http://injapan.no/energy2015-day2/)
    - Location: Omuta City, Fukuoka   Inside Mikawa Thermal Power Plant   (Property of SIGMA POWER Ariake Co.Ltd.)
    - Post Combustion Capture   Amine-based Chemical Absorption (Toshiba's Solvent System)
    - CO2 capacity: 10 ton-CO_2 / day
    - Flue Gas Flow: 2100 Nm3 / hour (from Coal Fired Power Plant).

South Korea

- Korean Electric Power Company (KEPCO) Research Institute
  - Two post-combustion test facilities at power plants on slip streams from 500 MW power plants operating on bituminous coal:
    - Boryeong 10MW Plant based on KEPCO RI Advanced Amine Absorbent; Captured CO_2 : 200 t-CO_2/day
    - Hadong 10 MW Plant based on KEPCO RI Solid Sorbent; Captured CO_2 : 200 t-CO_2/day.
- KIER has 2 MWe coal-fired power plant which provides spaces for lab scale CO_2 capture units that can be connected with real flue gas from coal-fired CFB boiler.
- Korea has also completed 1 MW warm gas clean-up test facility with 0.1 MW pre-combustion CO_2 capture test-bed slipstreamed from either 20 t-coal/d gasifier or later Taean 300 MW IGCC in September, 2015. These technologies for IGCC use solid sorbents and fluidized-bed processes.
  -

USA

- Big Bend Station (MIT):
  - Company/Alliance: Tampa Electric, Siemens
  - Location: Big Bend Power Station, Ruskin, Florida, USA
  - Feedstock: Coal
  - Size: 1 MW (slipstream from 1892 MW power station)
  - Capture Technology***:*** Post-combustion (Siemens POSTCAP technology).

- Plant Barry (MIT):
  - Company/Alliance: Southern Energy, Mitsubishi Heavy Industries (MHI), Southern Company, SECARB (US DOE's Southeast Regional Carbon Sequestration Partnership) and Electric Power Research Institute
  - Location: Plant Barry Power station, Mobile, Alabama, US
  - Feedstock: Coal
  - Size: Stage 1: 25 MW slip stream (0.15 Mt of CO2 captured annually)
  - Stage 2: 160 MW: 1Mt of CO2 /yr (TBD if phase 2 will go ahead)
  - Capture Technology: MHI amine based process called called KM-CDR, and utilizes MHIA's KS-1 solvent.

- Polk Station (MIT):
  - Company/Alliance: Tampa Electric, Siemens
  - Location: Big Bend Power Station, Ruskin, Florida, USA
  - Feedstock: Coal
  - Size: 30% side stream from 250 MW
  - Capture Technology: IGCC Pre-combustion (Siemens POSTCAP technology).

- E.W. Brown (MIT):
  - Company/Alliance: University of Kentucky Center for Applied Energy Research (UKCAER)
  - Location: Kentucky Utilities Company's E.W. Brown Generating Station, near Harrodsburg, Kentucky, USA
  - Feedstock: Coal
  - Size: 2 MW

- Capture Technology: Post-combustion, a new system testing an innovative heat integration method that will utilize waste heat from a carbon capture system for heat. The process also implements a concept with the heat integration that increases the solvent's CO2 capture rate and capacity in the scrubber.

9 Summary and Recommendations

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 in the order of 100 tonnes per day and more.

The study is based on a literature and web review of the status of emerging (2nd and 3rd generation) CO_2 capture technologies and existing test facilities. It was performed jointly by the CSLF Policy and Technical Groups. Neither the inventory of emerging technologies nor of test facilities can be regarded as complete.

Around 30 groups of 2nd and 3rd generation (emerging) CO_2 capture technologies have been identified. Most are 3rd generation, i.e. Technology Readiness Level (TRL) 1 – 3(4) and must be classified as tested at laboratory or bench scale only. A minority is classified as 2nd generation, i.e. TRL 4(5) – 6. The results are summarized in Table 1 below.

The table below summarizes 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. See Chapter 3.3 for reservations regarding the cost and energy consumption reduction potentials. Also note that cost reduction usually refer to reduction of Levelized Cost of Electricity (LCOE) but for some (high ones) it may only be for the capture component.

Green=Commercial
Yellow=2nd generation
Red=3rd generation
?=Uncertain estimates that are not quoted

Capture approach (Post-, pre- or oxy-combustion	Technology group	Generation/ Technology Readiness Level (TRL)	Potential for energy savings	Potential for cost reduction (in most cases reductions in LCOE)	Application (power and industry)
Post-combustion solvents	Amine-based solvents	Commercially available from several vendors (Shell Cansolv, Aker Solutions (earlier Aker Clean Carbon), Fluor, Mitsubishi Hitachi, Linde-BASF and Alstom)			
	Precipitating solvents	2nd-3rd/4-6	10-20% rel. MEA (2.3-3.6 GJ/t CO_2)	5-10%	Power, steel, cement
	Two-phase liquid system	2nd-3rd/4-5	2.0-2.3 GJ/t CO_2	5-10%	Power, steel, cement
	Enzymes	3rd/1-2(3)	30-35% rel. MEA (?)	5-10	Power, steel, cement
	Ionic fluids	2nd-(3rd)/1 – 4	15 -20 % rel.	?	Power, cement,

			MEA		steel
	Encapsulated solvents	3rd/1-2	?	?	Power, cement, steel
	Electrochemical solvents	3rd/1-2	Uncertain	Uncertain, may be none	Power, cement, steel, aluminium
Post-combustion sorbents	Calcium looping system	2nd/5-6	Coal: Efficiency penalties 5-10% Gas: no benefits	May be significant	Power, cement, steel
	Other looping systems	3rd/1-2	?	?	Power, steel, cement
	Vacuum Pressure Swing (VPS)	3rd/2-3	Uncertain, could be good	May be not	Power, cement, steel
	Temperature swing (TS)	3rd/1-2	Uncertain, appears limited	?	Power, cement, steel
Post-combustion membranes	Polymeric membranes	2nd/5-6	Fuel consumption: 50% down rel. MEA?	30% for capture component only?)	Power, cement, steel
	Polymeric membranes w/cryogenic	2nd/2-6	Better than above	30% for capture component only?)	Power, cement, steel
	Other membranes (electrochemical, ceramic and composites)	2nd - 3rd /2 - 4	?	?	Power, cement, steel
	Molten Carbonate Fuel Cells (electrochemical)	2nd – 3rd/3-4	Could result in efficiency higher than base power plant	90% capture increases cost of power by only \$0.02/kWh	Power, cement, steel
Post-combustion, other	Cryogenic (low temp)	2nd-3rd/3-5	Competitive MEA	Moderate ?	Power, cement, steel
	Supersonic	3rd/1-2	?	?	Power, cement, steel
	Hydrates	3rd/1-3	?	?	Power
	Algae	3rd/1-3	?	?	Power and most other industries
	CO_2-enriched flue gas	2nd/5-6	?	?	Power
	Pressurized post-combustion	2nd-3rd/2-5	?	?	Power
Pre-combustion 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-combustion sorbents	Sorption Enhanced Water Gas Shift (SEWGS)	2nd/4-5	Efficiency gain 3-4 %-points	30%	Power, (in combination with IGCC) refinery, H_2

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					production
	Sorption Enhanced Steam-Methane reforming (SE-SMR)	3rd/1-2	Appears limited in NGCC	?	Power, refinery, H_2 production
Pre-combustion membranes	Metal and composite membranes	2nd-3rd/3-5	Efficiency gain 3 %-points	May be as high as 25-30%	Power, refinery, H_2 production
	Ceramic membranes	2nd-3rd/2-4	As above?	May be up to 25% (for capture omponent ony?)	Power, refinery, H_2 production
Pre-combustion, other	Cryogenic (low temperature)	3rd/1-3	Efficiency gain 3-4 %-points; 1 GJ/t CO_2	May be as high as 30 – 50% (last w/recycle of CO_2)	Power, refinery, H_2 production
	Concepts with fuel cells	2nd-3rd/3-6	Efficiency gain up to 30 %-points rel. IGCC and gas w/MEA	> 70%	Coal and biomass power, refinery, H_2 production
Oxygen production for oxy-combustion	Cryogenic air separation	Commercially available			
Oxy-combustion	Chemical looping combustion	3rd/2-3	Efficiency gain 2-4 %-points (?)	Large	Coal power
	Pressurized oxy-combustion w/ Rankine Cycle	3rd/2-4	~35% efficiency	98% CO2 capture; cost of power 30% higher than without CCS – large cost reduction is 22+%	Coal and biomass power
	Pressurized oxy-combustion w/ Brayton Cycle	3rd/2-4	~38% efficiency	98% CO2 capture; cost of power 20% higher than without CCS – cost reduction is 32+%	Coal and biomass power
	Oxygen transporting membranes (OTM) power cycle	3rd/2-3	Efficiency gain 5 %-points over NCCC w/MEA(?)	?	Power

The potential for cost end energy consumption reductions vary from very small to significant in the above table. However, it is important to note that the numbers are based on a literature survey and may not be derived in a consistent manner. Furthermore, the technologies are at different levels of maturity, which will influence the uncertainties of the estimates. Factors that contribute to the uncertainties include:

- Comparison to different baselines (old, new, unfavourable, etc. in addition to different assumptions and battery limits)
- Cost unit (e.g. cost of electricity (COE), levelised cost of electricity (LCOE), cost per tonne CO_2 captured or abated
- First of a kind (FOAK) or nth of a kind (NOAK)
- Basically unfamiliar production methods and materials
- Reporting in efficiency changes (% relative some baseline) or energy requirements (GJ/tonne CO_2)
- Electricity vs. thermal energy
- Work vs. thermal energy
- Limited information and testing of emerging technologies.

It is important to be conscious of these uncertainties when choosing technologies for further development and testing.

The study has identified 11 test facilities for CO_2 capture technologies that are or will be independent of technology providers and that may be used to speed up the development of emerging capture technologies. Only two of these are sufficiently large to allow the next step in the technology development to be full scale. The other must be classified as small scale testing capabilities, i.e. < 10 000 tonnes CO_2/year or the equivalent of 2 MW coal fired power. These are often run on simulated flue gas. Testing at these smaller facilities will require at least one intermediate step before going to full scale. The majority of the identified test facilities are designed for post-combustion capture of CO_2.

There also several test or demonstration facilities for CO_2 capture technologies that are owned by technology providers to test specific proprietary technologies. These are in general not available for testing of other technologies. Some of these facilities are briefly described in the report.

The study revealed that the literature uses a range of definitions for technology maturity and test scales and sometimes inconsistent use of terms. For example, although it is difficult to avoid a gliding scale between the terms "pilot" and "demonstration" size facilities, a difference in terms of captured CO2 has been found to vary with almost 3 orders of magnitude and at least one order in terms of power.

Recommendations for Follow-Up by CSLF

Many technologies are developed by universities or small R&D companies that do not have the resources, financial and competence, to take the development further without support by others and access to one level larger test facilities. To progress the 2nd and 3rd generation CO_2 capture technologies further in a cost efficient manner CSLF should consider the following:

- Implement mechanisms that allow developers of emerging technologies and operators of test facilities to cooperate in mutual beneficial and cost effective ways, e.g. help establishing bi- and/or multi-lateral agreements and funding mechanisms that allow emerging technologies to be tested at another nation's facilities. The International Test Centre Network (ITCN) and the

European network ECCSEL initiatives are examples of how governments cooperate to increase testing capacities
- o Promote cooperation between facilities with different capabilities, both below and above 2MW or (10^4 tons CO_2/year, ~ 30 tons CO_2/day). This would increase the range of test opportunities and facilitate and accelerate knowledge sharing and exchange of experiences among member countries and between two or more test facilities
- o Based on the successful model of the ITCN and ECCSEL, CSLF should encourage and facilitate enhancing the networks to cover additional regions, sectors, and levels of scale. This would help to lay the ground to accelerate the development and testing of technologies in additional environments and facility configurations / conditions. As well, with increased membership, costs can be spread across a larger number of participants
- o Enhance opportunities for researchers and developers to participate in extended visits and staff exchanges to other demonstration projects and test centres (6 months or more) as well as training opportunities, much along the lines of the European initiative ECCSEL. This item should be coordinated with the re-established CSLF Academic Community Task Force.
- o Contribute to derivation of a consistent terminology for new CO_2 capture technologies, maturity (2nd and 3rd generation vs. emerging or transformational; consistent use of Technology readiness level, TRL) and for different testing scales (bench, lab, pilot, demonstration)
- o Contribute to derivation of consistent performance indicators, e.g. common methods for cost and energy consumption.

Acknowledgements

The following gave valuable comments to different versions of the draft report
- CSLF delegates from Australia, EC, France, Japan, South Africa, South Korea and Canada
- Åse Slagtern and Aage Stangeland at the Research Council of Norway (RCN)

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
CO2CRC	Australia's leading R&D Organisation for Greenhouse Gas Technologies
COURSE50	CO2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50
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

APPENDIX A - CO_2 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 based 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 associated 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 a net negative 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-T-2015-09
20 October 2015

TECHNICAL GROUP

Election of Technical Group Chair and Vice Chairs

Background

As stated in Section 3.3 (a) of the CSLF Terms of Reference and Procedures, CSLF Chairs and Vice Chairs will be elected every three years. The previous election of the Technical Group Chair and Vice Chairs was at the Perth meeting in October 2012, so the next election has been scheduled for the November 2015 CSLF Ministerial Meeting in Riyadh, Saudi Arabia.

Action Requested

The Technical Group is requested to hold an election to select a Chair and Vice Chairs whose terms will run through November 2018.

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Election of Policy Group Chair, Technical Group Chair, and Technical Group Vice Chairs

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

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

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

2. *Within one week after the closing date for nominations, the Secretariat should post on the CSLF website and email to Policy and Technical Group delegates as appropriate the names of Members nominated and identify the Members that nominated them.*

3. *As specified by Article 3.2 of the CSLF Charter, the election of Chair and Vice Chairs will be made by consensus of the Members.*

4. *When possible, regional balance and emerging economy representation among the Chairs and Vice Chairs should be taken into consideration by Members.*

On 04 August 2015, the Secretariat sent an e-mail to CSLF Policy Group delegates, informing them of the upcoming election of the Policy Group Chair, the Technical Group Chair, and the Technical Group Vice Chairs, and that nominations must be received by the Secretariat no later than six weeks prior to the meeting (i.e., by 21 September 2015).

The following nominations were received by the Secretariat:

<u>Policy Group</u>

- United States has been nominated for Policy Group Chair by Canada, China, the European Commission, Italy, Norway, and Russia.

<u>Technical Group</u>

- Norway has been nominated for Technical Group Chair by China, the European Commission, Italy, Russia, and the United States.

- Australia has been nominated for Technical Group Vice Chair by China, Italy, and the European Commission.
- Canada has been nominated for Technical Group Vice Chair by the European Commission, Italy, and the United States.
- Japan has been nominated for Technical Group Vice Chair by the United States.
- South Africa has been nominated for Technical Group Vice Chair by the European Commission and the United States.
- United Kingdom has been nominated for Technical Group Vice Chair by China.

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF-P-2015-04
Draft: 19 October 2015
Prepared by CSLF Secretariat

Draft Minutes of the Policy Group Meeting
Regina, Saskatchewan, Canada
Friday, June 19, 2015

LIST OF ATTENDEES

Chair	Christopher Smith, United States

Policy Group Delegates

Australia:	Maxwell Watson
Canada:	Geoff Murphy, Kathryn Gagnon, Eddy Chui
China:	Sizhen Peng, Xian Zhang
European Commission:	Jeroen Schuppers
Japan:	Takashi Kawabata, Ryozo Tanaka
Korea:	Chang Keun Yi, Chong Kul Ryu
Mexico:	Hector Castro, Jasmin Mota
Norway:	Tone Skogen, Trygve Riis (Technical Group Chair), Lars Ingolf Eide
Poland:	Anna Madyniak
Saudi Arabia:	Khalid Abuleif, Hamoud AlOtaibi, Ahmed Aleidan, Fahad Almuhaish
South Africa:	Landi Themba
United Kingdom:	Tony Ripley
United States:	Mark Ackiewicz, Stephanie Duran

Representatives of Allied Organizations

Global CCS Institute:	Victor Der, Pamela Tomski
IEA:	Tristan Stanley
IEAGHG:	Tim Dixon

CSLF Secretariat

Jarad Daniels, Richard Lynch, Adam Wong

Invited Speakers and Distinguished Guests

Michael Marsh, President and CEO, SaskPower, Canada
Michael Monea, President, Carbon Capture & Storage Initiatives, SaskPower
Trygve Riis, Technical Group Chair, Norway
Edward Rubin, Department of Engineering and Public Policy, Carnegie Mellon University, United States
Barry Worthington, United States Energy Association, United States

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Observers

Canada:	Richard Adamson, Chunjiang An, Sandra Beingessner, George William Sherk, Jason Toner, Floyd Wist, Ian Yeates, Zewei Yu
China:	Jinfeng Ma, Hong Wang, Wei Wang
Korea:	Sung Ho Jo
United Kingdom:	Aatif Baskabderi, Bill Buschle
United States:	Edward Dodge, Katherine Romanak

1. Welcome and Opening Statement

Christopher Smith, Policy Group Chair, United States, called the meeting to order and thanked Michael Marsh and his team at SaskPower for the week's events. Mr. Smith also acknowledged the hard work of the Policy Group, Technical Group, Stakeholders, and CSLF Secretariat. Mr. Smith reinforced his view that the success of the CSLF is dependent on how closely the CSLF Policy Group and Technical Group work together, as this provides the critical direction the CSLF needs to more effectively advance carbon capture and storage (CCS). Mr. Smith made note of the upcoming 2015 CSLF Ministerial Meeting and the 2015 United Nations Climate Change Conference (COP21), and stressed that CSLF collaboration will become even more important.

2. Meeting Host's Welcome

Michael Marsh, President and CEO, SaskPower, welcomed everyone to Regina, Saskatchewan, Canada. Mr. Marsh acknowledged the important discussions that have taken place during the week's events. He noted that SaskPower's work in CCS came from a need to maintain their coal fleet, which provides a reliable and affordable source of their electric supply mix. As the Saskatchewan province was growing, they needed to support this growth, but in an environmentally responsible way. SaskPower is helping advance CCS knowledge and technology through both SaskPower's flagship CCS initiative, the Boundary Dam Integrated CCS Project, and also the recent opening of their Shand Carbon Capture Test Facility (CCTF). CCTF will allow testing of new and emerging CCS technologies that can be applied around the world. Mr. Marsh referred to a recent speech by Christiana Figueres, Executive Secretary of the UN Framework Convention on Climate Change (UNFCCC), who referred to CCS as a very important technology where not enough investment is taking place. He noted that the CSLF has a very important role to play in championing the investment in CCS. Mr. Marsh stated that he looked forward to the continued good work of the CSLF, as they work to continue to support the future of CCS around the world.

3. Introduction of Delegates

Policy Group delegates introduced themselves. Thirteen of the twenty-three CSLF Members were present, including representatives from Australia, Canada, China, European Commission, Japan, Korea, Mexico, Norway, Poland, Saudi Arabia, South Africa, the United Kingdom, and the United States. Observers representing the Global CCS Institute, International Energy Agency, the IEA Greenhouse Gas R&D Programme (IEAGHG), Canada, China, Korea, the United Kingdom, and the United States were also present.

4. Adoption of Agenda

The Agenda was adopted without change.

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5. **Review and Approval of Minutes from Warsaw**
The Minutes from the CSLF Policy Group Meeting on October 30, 2014, in Warsaw, Poland were approved without change.

6. **Review of Warsaw Meeting Action Items**
Jarad Daniels, Director, CSLF Secretariat, provided a brief summary of the action items from the CSLF Policy Group Meeting on October 30, 2014, in Warsaw, Poland. All action items have been completed or were to be completed during the day's meeting.

7. **Report from CSLF Technical Group**
Trygve Riis, Technical Group Chair, Norway, provided an update from the CSLF Technical Group. At the Technical Group Meeting on June 16, 2015, the Technical Group voted to recommend the Shaanxi Yanchang Petroleum Group's Jingbian CCS Project in China to the Policy Group for CSLF recognition. Nominated by China and Australia, the Jingbian CCS Project is an integrated project including capture, transport, and storage, along with a comprehensive measurement, monitoring and verification (MMV) regime for both surface and subsurface monitoring of the injected CO_2. This pilot-scale project started in 2012 in the Shaanxi Province, China, and captures CO_2 from a flue gas slipstream of a coal-to-chemicals facility (50,000 tonnes per year with increase to 370,000 t/y) for utilization in multiple injection sites for enhance oil recover (EOR) at the Jingbian Oil Field in the Ordos Basin.

The Technical Group also reviewed the initial draft of the Technology Roadmap (TRM), with the final version expected to be a deliverable for the 2015 CSLF Ministerial Meeting. The draft TRM will now be redrafted, with the CSLF Secretariat leading the initial rewrite. The Technical Group also reviewed the progress of the joint Policy Group-Technical Group Task Force on "Supporting Development of 2nd and 3rd Generation CCS Technologies," and the Technical Group Task Force on "Sub-Seabed CO_2 Storage" will have a final report by the 2015 CSLF Ministerial Meeting. Finally, the Technical Group also formed a working group to develop new activities for the Technical Group's Action Plan, which will include participation from Australia, Norway, Saudi Arabia, the United Kingdom, the United States, and Japan (invited), with coordination by the CSLF Secretariat.

After the update from Mr. Riis, the Policy Group voted to approve the Jingbian CCS Project for CSLF recognition.

8. **Report from the CCS in the CCS in the Academic Community Task Force**
Edward Rubin, Department of Engineering and Public Policy, Carnegie Mellon University, provided a report on the CCS in the Academic Community Task Force. This 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 the CSLF in this area. However, the Task Force has not been active since the 4th CSLF Ministerial Meeting in 2011. It was agreed that the U.S., and potentially Mexico, will co-lead the Policy Group's effort to reestablish this Task Force with a focus on fostering and supporting international CCS collaborations, international research exchanges, CCS summer schools and short courses, and international networks. The motivation is that many governments do not have the

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mechanisms to support such activities, and that programs that do exist are mostly ad hoc and not coordinated to maximize benefits. The goal of the Task Force will be to establish a network and provide a report summarizing findings and recommendations, to be delivered at the 2015 CSLF Ministerial Meeting. After the discussion, potential other members of this Task Force included Canada, Poland, Saudi Arabia, South Africa, the United Kingdom, and the Global CCS Institute.

9. Assessing Barriers to High-Level Geological CO_2 Storage

Tony Ripley, United Kingdom, provided an update on the U.K.-Korea project to identify barriers to geological CO_2 storage assessments. This initiative was funded by the U.K. and Korea, and emerged from the Clean Energy Ministerial (CEM) CCUS Action Group over the concern that many countries have not assessed their potential storage capacity in sufficient detail. This project was delivered by the British Geological Survey (BGS) with help from IEAGHG. The BGS sent out a questionnaire to a wide range of contacts in March. These questions were on topics such as storage assessments completed or underway; comparison of methodologies used; and plans for, and barriers to, further assessments. The aim is to complete the work this year and present findings at a workshop. All of the responses received thus far had some level of storage assessment in their country, and the nature of the assessments so far reported vary from theoretical to matched storage. Most of these assessments have been at a sedimentary basin level (52%), with 38% covering offshore territory. While responses have come from across the globe, there are still some gaps, so it would be useful to have more responses to ensure as wide an evidence base as possible.

10. Discussion of Exploratory Committee Work Plan Status:

a. Financing for CCS Projects

Due to a last minute issue, Bernard Frois, France, was unable to attend the meeting and had sent his sincere apologies and regrets. Jarad Daniels, CSLF Secretariat, led the discussion in his place. In recent years, the Financing for CCS Projects Task Force has led a series of workshops to engage the financial community and foster the dialogue with project developers to better understand a strong business case for CCS projects. This has also led to an exchange of information from the CCS community, specifically from major project proponents, to the financial community to get more comfortable with the fact that CCS is a maturing technology. A variety of options were discussed over how to best present the work of the Financing for CCS Projects Task Force to the Ministers at the 2015 CSLF Ministerial Meeting. Suggestions included a roundtable of successful financing business cases for CCS projects that are operational, in order to highlight the success stories. It was also suggested to include CCS projects that are close to moving forward on construction, along with what regulatory environments can help push projects into a final decision. The CSLF Secretariat will take the action to work with France and the CSLF Ministerial Steering Committee to frame the financing and business case discussions at the 2015 CSLF Ministerial Meeting.

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

Trygve Riis, Technical Group Chair, Norway started the discussion regarding the work done with Canada as co-leads for the Supporting Development of 2nd and 3rd Generation CCS Technologies Task Force, a joint effort between the Technical Group and Policy Group. Mr. Riis provided a summary and turned it over to Lars Ingolf Eide, Norway, who had prepared and presented a draft report from the Task Force. Mr. Eide explained that the work had been separated into two groups, where the Policy Group is responsible to map initiatives and funding mechanisms for 2nd and 3rd generation technologies in CSLF member countries, along with preparing a policy document on how to achieve an accelerated implementation of 2nd and 3rd generation CO_2 capture technologies. The Technical Group is responsible to map and identify 2nd and 3rd generation technologies, including those that may be mature in the 2020 –2030 timeframe, development plans to scale from current readiness, and major challenges facing technology development. The Technical Group will also use existing networks to map potential for testing 2nd and 3rd generation technologies at existing test facilities. Next steps for the Technical Group include a quality check of the 2nd and 3rd generation report, and also complete information gathering on test facilities.

Geoff Murphy, Canada, presented a proposal on how the CSLF can track the development of 2nd and 3rd generation. This proposal includes the creation of a new section of content on the CSLF website. The main purpose will be to provide a neutral, fact-based information hub for identifying and tracking the progress of 2nd and 3rd generation technologies occurring within CSLF member countries.

Kathryn Gagnon, Canada, spoke on how the Task Force has done research to focus on the mechanisms for accelerating the adoption of 2nd and 3rd generation carbon capture technologies. Over 35 individuals were interviewed from about 30 organizations in 8 CSLF countries and the European Union. These interviewees advised on key barriers, existing mechanisms that work to accelerate next generation carbon capture technologies, insights on success factors and areas for improvement, and the highest priorities for mechanisms that should be the top priorities for policy makers. Common feedback from interviewees included that it is well-recognized that market drivers are lacking for CCS, and that the success of 1st generation CCS is a key driver for next generation, as 1st generation CCS knowledge offers tremendous value to next generation technology developers. Other common themes included that government funding programs are generally highly regarded, and that test centers were identified as essential by many stakeholders, since they can accelerate the time to deployment and vastly reduce the costs.

After a discussion, it was agreed that Canada and Norway will develop a short executive summary and recommendations for supporting 2nd and 3rd generation research and development (R&D), which will be used to provide input for the Ministerial Communiqué and allow the CSLF Ministerial Steering Committee to shape this aspect of the 2015 CSLF Ministerial Meeting. This document can also potentially be a deliverable to the Ministers.

c. Global Collaboration on Large-Scale CCS Projects

Jarad Daniels, United States, provided an update on the work of the Large-Scale CCS Projects Task Force. It had previously been determined that the CSLF is well-positioned to facilitate discussions on global collaboration efforts for large scale CCS projects, whether as new green field projects or by adding additional functionality and value to existing or planned commercial projects. An important factor in approving this initiative was the focus of most ongoing large-scale CCS projects on the use of captured CO_2 for EOR. There was a consensus, however, that storing CO_2 in deep saline formations will ultimately be the most important CCS option for achieving major CO_2 emissions mitigation.

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At the last CSLF Policy Group Meeting on October 30, 2014 in Warsaw, the Task Force was tasked to develop a preliminary list of candidate projects evaluated against initial selection criteria. The Large-Scale Integrated Projects (LSIP) data base published by the Global CCS Institute (GCCSI) was screened to identify projects, and five projects met the criteria, of which two nearer-term, high CO_2 capture volume projects: the Quest CCS Project and the Illinois Industrial CCS Project, which are both carrying out or planning aggressive R&D at their sites, and have indicated an interest in collaboration.
It was agreed that the Task Force will proceed with the Quest CCS Project and the Illinois Industrial CCS Project as part of a saline storage test network. CSLF members should be consulted to determine interest in providing support to a test center, and when support could become available. Additional candidate sites should be proposed whenever they are considered by the host country to be viable network candidates.

It was agreed that the U.S. and China should continue to lead the direction of the Large-Scale CCS Projects Task Force. Other networking opportunities could include potentially an International CCS Demonstration Project Knowledge-Sharing Network, a Saline Storage Test Network, a Geomechanics/Induced Seismicity Research Network, an Offshore Carbon Storage Test Facility, or a Non-EOR CO2 Utilization Research Network. These additional potential collaborative efforts could be done through the CSLF Technical Group or with the IEA GHG Programme. The Task Force will work with the Ministerial Steering Committee to determine the best way to present this effort at the 2015 CSLF Ministerial Meeting.

d. Communications

Hamoud AlOtaibi, Saudi Arabia, provided an update on the CSLF Communications Task Force. Over the past year, the Task Force has delivered key CCS messages to parties ahead of a number of major clean energy meetings and conferences. The Task Force has also a scope of work for a communications professional to develop a CSLF communication strategy. Mr. AlOtaibi outlined the key events on the road to the COP21 meeting in Paris towards the end of 2015. It was suggested that the role of the CSLF at the COP21 will be to provide messages to delegates, participate in side events and briefings, and have a stall at exhibition areas. In the lead up to the 2015 CSLF Ministerial Meeting, the Communications Task Force plans to continue to support development of the CSLF Ministerial Communiqué, communicate the importance of CCS to guest countries, seek new CSLF members, host a potential exhibition at the Ministerial event, and promote CCS projects around the world.

It had been previously proposed at the CSLF Policy Group Meetings in both London and Warsaw that a communication professional should be engaged to develop and support a comprehensive CSLF communication strategy. This scope would include promoting CCS through communiqués and announcements at high profile events, coordinate individual member messages outside CSLF official communications, build on existing agreed CSLF messages and positions, and develop a strategy based on the opportunities and events in the period leading to COP21. This scope was drafted by the Global CCS Institute, and Saudi Arabia has agreed to provide funding. It was agreed to that the Communications Task Force should proceed to engage a communications professional to develop and support a comprehensive CSLF communications strategy, with support from Saudi Arabia.

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11. Stakeholder Recommendations to CSLF

Barry Worthington, United States Energy Association, United States, spoke on behalf of the CSLF Stakeholders. Mr. Worthington first discussed reflections from the Stakeholders perspective post the CSLF Ministerial Meeting on November 7, 2013 in Washington, D.C. The CSLF experienced a rejuvenation at this Ministerial, and now sits in a different position than it did before the meeting, as finance, regulation, and communication were all important topics. The biggest message from the 2013 CSLF Ministerial was that fossil fuels are here to stay, and that CCS has to be an important component of any climate change strategy. Without CCS, the world will not meet its climate change goals. Fossil fuels will be necessary to pull people out from energy poverty and to help other people who do not have affordable, reliable access to energy. CCS contributes to energy affordability by meeting climate goals, but also contributes to energy security, system resiliency, and operation ability. Some of the specific recommendations made were that governments should help the private sector drive down the costs, governments should focus on removing barriers to reaching final investment decisions, and governments should consider policy parity for CCS. It was also suggested that communications from the CSLF should also be improved, and that improvement has already been seen since the 2013 CSLF Ministerial. Stakeholders also expressed their commitment to the CSLF.

Mr. Worthington then offered some general preliminary thoughts on Stakeholder participation at the upcoming 2015 CSLF Ministerial Meeting in Riyadh, Saudi Arabia. The Stakeholders expressed a desire to see some continuity with the upcoming 2015 CSLF Ministerial Meeting, and would like to again see a CSLF Stakeholder focus on finance, regulation, and communication. USEA will coordinate the participation from Stakeholders, including events and discussions to be coordinated with the Ministerial agenda. The CSLF Ministerial agenda will include a Stakeholder message to the CSLF Ministers.

Mr. Worthington then also informed the CSLF Policy Group of some of the important CCS related activities that the Stakeholders have been engaged with in the United Nations Economic Commission for Europe (UNECE). Christian Friis Bach, Under-Secretary-General of the United Nations, & Executive Secretary of the UNECE, provided UNECE recommendations to the UNFCCC which included an endorsement of CCS as a need to limit global warming due to the use of fossil fuels.

12. Report from the CSLF Capacity Building Governing Council

Tone Skogen, Capacity Building Governing Council Chair, Norway, summarized the status of the CSLF Capacity Building Program. The CSLF Capacity Building Fund was established by the CSLF Ministers at the 2009 CSLF Ministerial in London, and contributions committed total US $2,965,143.75, with donors from Australia (via the Global CCS Institute), Canada, Norway, and the United Kingdom. As of now, US $1,984,409 has been committed for 14 approved capacity building projects in 5 countries. Of the 14 approved projects, 10 have been completed and 4 are to be negotiated or revised. On February 24, 2015, the CSLF Capacity Building Fund monies were transferred from the United States Department of Energy to the Global Carbon Capture and Storage Institute (the Institute), which triggered the Institute's role as the CSLF Capacity Building Fund Manager. The funds currently available for allocation are US $924,072.80 (AU $1,180,169.60), and the Governing Council will soon send out a request for submissions for the remaining available funds for new projects. It was also agreed that the Capacity Building Governing Council will work with CSLF Ministerial Steering Committee to determine how best to showcase capacity building successes, lessons learned, and opportunities going forward. It was noted that CCS capacity building in academia may represent low-hanging fruit opportunities to pursue in coordination with the CCS in the Academic Community Task Force.

Landi Themba, South Africa, provided a presentation titled, "Carbon Capture and Storage in South Africa and Inflated Salary Packages of International CCS Experts." In this presentation, Mr. Themba provided an overview of CCS in South Africa, which is a significant polluter as approximately 90% of its primary energy is derived from fossil fuels. South Africa is preparing for a Pilot Carbon Storage Project (PCSP), scheduled for 2017 to inject about 10,000 tonnes of CO_2 in the Kwa-Zululand Basin, a South African geological formation. The estimated cost for the PCSP is likely to range from R500 million to R1.6 billion. The World Bank is a key contributor to the PCSP, and derives its funding from countries like Norway and the U.K. However, Mr. Themba emphasized that developing countries like South Africa have no continual annual budget dedicated to CCS, and in the case of the PCSP, international CCS experts they approached to provide skills transfer, training, and mentorship, demanded inflated salary packages. Thus, South Africa is seeking CSLF intervention in providing guidelines on salary packages for CCS experts and advisors. The CSLF recommended that South Africa consider submitting a CSLF Capacity Building Project request for funds, as this could be one path forward to build the capacity of members such as South Africa.

13. Report on UNFCCC Bonn Climate Change Conference

Khalid Abuleif, Saudi Arabia, provided a report on the UNFCCC Bonn Climate Change Conference, held from June 1-11, 2015 in Bonn, Germany. Mr. Abuleif stated the importance of this meeting in the road to the COP21 later this year. A number of meetings have been held during the past year, and a draft text has been developed for COP21, with the objective being to achieve a legally binding and universal agreement on climate, from all the nations of the world. During the past year, the draft text has been revised, and will continue to be reviewed in a number of upcoming meetings. Everyone is determined that a real solution will be reached in time for COP21.

14. Planning for 2015 CSLF Ministerial Meeting

Fahad Almuhaish, Saudi Arabia, provided an update on planning for the 2015 CSLF Ministerial Meeting, which will take place November 1-5, 2015 in Riyadh, Saudi Arabia. From November 1-4, the meeting will take place in Riyadh and include CSLF Meetings and a carbon capture, utilization, and storage (CCUS) exhibition. On November 5, a Saudi Aramco tour will include a visit to Dhahran and include a demonstration, virtual broadcast, and site visits. Over 50 Ministers and 5-10 CEOs have been invited. Mr. Almuhaish provided a proposed Ministerial Meeting Agenda, which would include two roundtables with public and private participation. Suggested topics and themes were discussed, and these topics and themes will be reviewed and selected by the CSLF Ministerial Steering Committee. The purpose of the Dhahran tour is to showcase pilot demonstration plants for CO_2 capture, CO_2-EOR and CO_2 utilization in the chemical industry; demonstrate research and innovation on CCUS; and show core oil and gas capabilities for delivering affordable energy to the world in a sustainable manner.

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15. Ministerial Communiqué

Jarad Daniels, Director, CSLF Secretariat, led the discussion regarding the draft CSLF Ministerial Communiqué. The hope is that the 2015 CSLF Ministerial Meeting can reenergize global momentum for CCS, and show that CCS is a reality and happening now. Suggested topics to incorporate into the Communiqué included collaboration on large scale projects, the role of EOR and utilization, enhanced water recovery, and lowering the barriers for policy parity for CCS. It was suggested that the Communiqué should not focus on a forced message of a need for policy parity, but rather a positive offer from CCS to publicize on the near-term opportunities and the many benefits CCS can bring. Other thoughts included highlighting work being done in the CSLF and to consider how to incorporate the concept of off-shore storage, public acceptance, non-EOR utilization, sustainability, and global collaboration with the IEA and Global CCS Institute. It was agreed that the Ministerial Steering Committee and the CSLF Secretariat will continue to push forward toward the CSLF Ministerial Meeting and developing the Communiqué, while communicating with the Policy Group at large as needed.

16. Open Discussion and New Business

No new business was discussed.

17. Action Items and Next Steps

Jarad Daniels, Director, CSLF Secretariat provided a summary of the day's Policy Group Meeting, and noted the significant recommendations and action items. The Policy Group reached a consensus on the following items:

- The Jingbian CCS Project was approved for CSLF recognition
- Working closely with the Technical Group, the U.S. and potentially Mexico, will co-lead the Policy Group's effort to reestablish the CCS in the Academic Community Task Force

Action items from the meeting are as follows:

Item	Lead	Action
1	United States	On behalf of the CCS in the Academic Community Task Force, provide a report summarizing findings and recommendations, to be delivered at the 2015 CSLF Ministerial Meeting.
2	CSLF Secretariat	Work with France and the CSLF Ministerial Steering Committee to summarize the "Financing for CCS Projects" work, and frame the financing and business case discussions at the 2015 CSLF Ministerial Meeting
3	Canada and Norway	As co-leads for the Supporting Development of 2nd and 3rd Generation CCS Technologies Task Force, develop a short executive summary and recommendations, to use to finalize the document to provide at the 2015 CSLF Ministerial Meeting

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Item	Lead	Action
4	U.S. and China	Continue to lead on the Global Collaboration on Large-Scale CCS Projects Task Force, while also pursuing other networking opportunities for further discussion at the next Policy Group Meeting. Work with the CSLF Ministerial Steering Committee to determine the best way to present this effort at the 2015 CSLF Ministerial Meeting.
5	Saudi Arabia, Global CCS Institute, IEA	As part of the Communications Task Force, proceed to engage a communications professional to develop and support a comprehensive CSLF communications strategy
6	CSLF Stakeholders	USEA, on behalf of the CSLF Stakeholders, will coordinate stakeholder events and discussions at the 2015 CSLF Ministerial Meeting. These discussions will be focused on three key topics: finance, regulations, and communications, and will be integrated with the 2015 CSLF Ministerial Agenda and include a Stakeholder message to the Ministers.
7	CSLF Capacity Building Governing Council	Work with the CSLF Secretariat to send out a request for submissions for the remaining available funds for the CSLF Capacity Building program, which is a little less than U.S. $1 million
8	CSLF Capacity Building Governing Council	Work with the CSLF Ministerial Steering Committee to determine how best to showcase capacity building successes, lessons learned, and opportunities going forward
9	CSLF Ministerial Steering Committee	Continue to push forward with planning toward the 2015 CSLF Ministerial Meeting, while communicating with the Policy Group at large as needed

18. Closing Remarks / Adjourn

Christopher Smith, Policy Group Chair, United States, provided the closing remarks. Mr. Smith reiterated thanks from the CSLF to the hosts, SaskPower, for the great venue and tremendous hospitality. He expressed his optimism for the future, as the CSLF is well-positioned to not only move CCS technologies, but also move the commercial and regulatory environments that will allow CCS technologies to be adapted, built, and contribute to the important mission to reduce greenhouse gas emissions down to sustainable levels. Mr. Smith thanked all participants for their contributions and adjourned the meeting.

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CSLF-P-2015-06
26 October 2015

POLICY GROUP

Application of Romania for CSLF Membership

Background

On 20 October 2015, Romania's Minister of Energy, Small and Medium Enterprises, and the Business Environment, the Honourable Andrei Gerea, sent a letter to the CSLF Secretariat that requested CSLF Membership for Romania. The CSLF Terms of Reference and Procedures states that in their letter of application, prospective CSLF 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 Secretariat has reviewed the letter from Minister Gerea and has determined that Romania has met all of these requirements.

Action Requested

The Policy Group is requested to approve the application for CSLF Membership from Romania.

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MINISTRY OF ENERGY, SMALL AND MEDIUM ENTERPRISES AND THE BUSINESS ENVIRONMENT

MINISTER CABINET

October 20, 2015

Hr. 103985

CSLF Secretariat
U.S. Department of Energy
FE-27
1000 Independence Ave., S.W.
Washington, DC 20585
U.S.A.

Dear Honorable Secretary, Ernest MONIZ

I am writing to submit this letter as application for Romania's membership in the Carbon Sequestration Leadership Forum (CSLF). Romania's qualifications for membership will be highlighted below.

Romania is in an enviable position with regard to energy. Romania is the third most energy independent country in the European Union with a diversified and the most balanced energy mix in the Union. It is endowed with significant energy resources, including natural gas, oil and coal, renewables and uranium. **The country has a long standing production of coal and oil and gas, stretching back more than 150 years.** Romania's entire hard coal and lignite output is used for heat and power generation. However, most of the lignite fueled generation assets are nearing their decommissioning dates. Given lignite's role in ensuring the country's energy security through maintaining a diversified energy mix, the Romanian Government is actively exploring advanced fossil energy technologies that would allow for the efficient use of lignite in a manner that meets EU and national climate and environmental goals.

Furthermore, the lignite industry in Romania is concentrated in a single geographical area where economic growth is highly dependent on the long-term outlook for mining and lignite utilization. Thus, any technology that can allow for the continued use of lignite in a manner that meets social, economic, environmental, climate, and energy security goals is of paramount interest. As part of the national priorities for energy and climate change, carbon capture and storage (CCS) plays a key role in ensuring Romania's ability to maintain a balanced energy mix and create a competitive economy while it pursues ambitious decarbonization goals.

For Romania, CCS offers the potential to radically reduce CO_2 emissions from large point sources such as coal- and gas-fired power plants and energy-intensive industrial facilities. CO_2 emissions from fossil generation, representing 43% of total CO_2 emissions in 2008, will need to be reduced for Romania to meet its climate obligations. The Romanian government used climate change goals as a mechanism for capacity building at an institutional level, proactively seeking EU funds for technology demonstrations. The National Reform Program 2011-2020 highlights CCS as a key area of research and development. The National Program for Carbon Capture and Storage seeks to develop the technology, reducing cost and paving the way for its implementation. Initiatives such as the "Action Plan to implement a Demonstration

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Project regarding Carbon Capture and Storage in Romania" have established the steps necessary to develop a CCS project in Romania, recruiting national and private bodies with the relevant skills.

Romania is rapidly becoming a regional leader in tackling climate change and looking into the future for appropriate technologies to achieve these goals. The deployment of CCS technologies in Romania can support local economic development, environmental and climate performance, and energy and national security, especially when the utilization of CO2 is considered. Romania could benefit from multiple opportunities for CO_2 utilization, ranging from utilization in the oil and gas industry to utilization as feedstock for industrial processes resulting in value added products such as urea fertilizers or methanol, or for use in food processing. The multiple economic and energy security benefits Romania can enjoy from developing all or part of the value chain surrounding CCUS projects further serves to enhance its national and economic security.

Romania's ageing infrastructure will need to be rapidly replaced and sustained investments over the coming decades will be required to maintain capacity and meet demand growth. Building an energy and industrial system fit for purpose is rapidly becoming ever more difficult with the necessary integration of new technologies to mitigate climate change and other pollution control measures coupled with the need to maintain economic competitiveness and mitigate negative social impact of associated with this transformation. As such, the possibility to repower the Romanian energy system is a once in a generation opportunity and well-informed decisions now could place the energy sector and the economy at large on a secure footing to meet the demands of this century. Through participation in forums for international cooperation, such as the CSLF, Romania seeks to create a competitive economy, based on innovation and fueled by a world-leading generation system.

Romania has a history of first mover and innovator in energy. Romania is the first country in the world with a petroleum production officially registered in the international statistics in 1857, build the world's first large refinery at Ploiesti in 1856-1857, its capital became the world's first city publicly illuminated with kerosene in 1857, and in 1884 the streets of Timisoara became the first in Continental Europe to be illuminated by electricity. As the 21st century is shaped by the third industrial revolution, through international cooperation Romania seeks to transform the need to balance energy, economic, and climate goals into opportunities for innovation in technology, institutions, markets, and policies.

With this in mind, I respectfully submit Romania's request to for membership in the Carbon Sequestration Leadership Forum and stand ready to contribute to the Forum's major role in averting global climate change.

Sincerely,

Andrei Dominic GEREA
Minister of Energy, Small and Medium Enterprises, and the Business Environment
Romania

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-P-2015-07
28 October 2015

POLICY GROUP

CCS in the Academic Community Task Force Report – Baseline Survey and Plan of Action

Background

At the June 2015 CSLF Mid-Year Meeting in Regina, the CCS in the Academic Community Task force was re-started with a near-term goal of identifying and engaging academic programs on CCS throughout the world. The task force was requested to provide a report summarizing its findings and recommendations, to be delivered at the 6th CSLF Ministerial Meeting.

Members of the task force are Canada, Poland, Saudi Arabia, South Africa, the United Kingdom, the United States, and the Global CCS Institute. Pamela Tomski of the Global CCS Institute was lead author and organizer of the following report from the task force.

Action Requested

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

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CCS IN THE ACADEMIC COMMUNITY TASK FORCE
CARBON SEQUESTRATION LEADERSHIP FORUM

Baseline Survey and Plan of Action

Mechanisms for International CCS Academic Collaborations,
Key Research Groups, Summer Schools and Networks

October 2015

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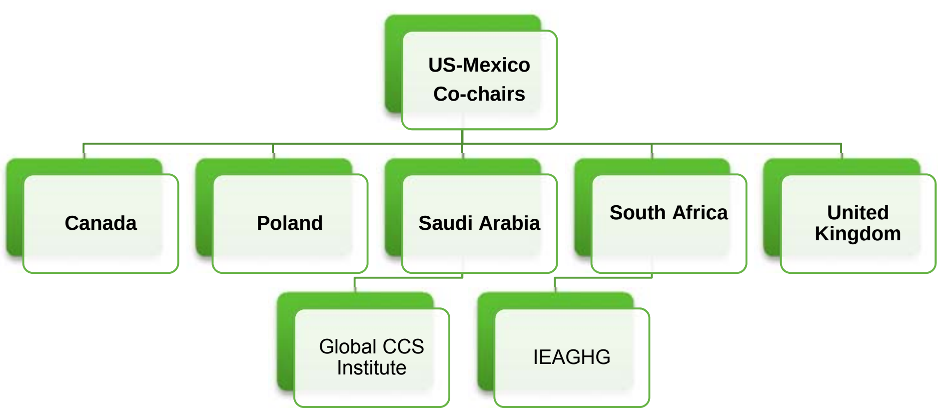
1 Introduction

The academic community plays a vital role to advance carbon capture and storage (CCS) technologies through research, development, and demonstration (RD&D), as well as through policy guidance and a wide range of educational programs that support development of the next generation of scientists, engineers and policymakers. Governments can strongly influence the extent to which the academic community is engaged in CCS. Thus, the Carbon Sequestration Leadership Forum (CSLF) is in a unique position to catalyze, grow and strengthen the academic community's contribution to achieving CSLF goals.

The mission of the *CCS in the Academic Community Task Force* (Academic Task Force), originally established in 2008, is to identify and engage academic programs on CCS throughout the world to help support the mission and path forward for the CSLF. Early accomplishments of the Task Force included a mapping and gap analysis of CCS post-graduate academic courses worldwide and links to the CSLF Capacity Building Task Force.

Although in recent years this Task Force has been dormant, at the CSLF Mid-Year Policy Committee Meeting in Regina, Saskatchewan, Canada in June 2015, it was re-established with a new organizational structure (Figure 1) and focus– to foster and support the CSLF mission and objectives via academic CCS research programs, international collaborations, research exchanges, networks, and summer schools. With more proactive engagement among the CCS academic community, the CSLF can facilitate international research collaborations in priority areas and leverage funding opportunities that advance the CSLF mission.

Figure 1: CSLF CCS in the Academic Community Task Force Members (June 2015)



Specifically, in re-establishing the Academic Task Force, its members agreed to take the following steps:

- Conduct a baseline survey of current CCS academic research programs, international collaborations, student exchanges, summer schools, and networks.

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- Assess current funding commitments and mechanisms in CSLF member countries to support and enhance international CCS academic collaborations.

- Determine funding opportunities available from capacity development programs such as the World Bank CCS Trust Fund, Asian Development Bank CCS Trust Fund, CSLF Capacity Development Fund and other sources.

- Assess resource needs to strengthen and catalyze Academic Task Force activities and determine opportunities to leverage available funding.

- Outline a plan of action for the Academic Task Force to help achieve CSLF goals.

In response to the above agenda set forward by the new Task Force, this report provides an initial baseline survey of existing mechanisms for international CCS academic collaborations, key research groups, summer schools, and networks for Academic Task Force members. The report also includes key CCS academic contacts for Task Force members, and presents a Plan of Action to strengthen Academic Task Force activities, as summarized below. This report will soon be expanded to include all CSLF member countries.

1.1 Plan of Action: Key Highlights

- Secure endorsement from Ministers at the CSLF Ministerial Meeting in Saudi Arabia in November 2015 on the importance of the CCS academic community to help meet CSLF goals, and the new structure of the CCS in the Academic Task Force.

- Secure endorsement from Ministers at the November CSLF Ministerial Meeting to provide support for the Academic Task Force to host a planning workshop for the CCS academic community some time in the first half of 2016, possibly in conjunction with the mid-year CSLF meeting. This Academic Task Force workshop will bring together academic representatives from the Task Force member countries, as well as other CSLF member states. The major objectives of the workshop are to:

    - Identify and document current academic community research linkages with CSLF Technical Group and Policy Group priorities;

    - Determine where and how the CSLF can help leverage international collaborations, student exchanges, summer schools, networks and funding opportunities to further CSLF goals;

    - Establish Academic Task Force membership across the global academic community, and

    - Prepare an Action Plan for moving forward, to be presented at the CSLF 2016 Mid-Year Meeting.

Required support for this workshop includes basic travel expenses for up to 20 academic participants from CSLF member countries (and potential member countries) who would not otherwise be able to attend.

- In addition to the above, the Task Force will undertake the following activities:

    - Complete baseline survey for all CSLF Member Countries; where there is no current activity, determine possible mechanisms and opportunities.

    - Assess current CCS internship opportunities with governments and industry and how they may be expanded among CSLF member countries and linked to study-abroad programs.

    - Assess the availability of on-line CCS certification programs and CSLF member interest in providing such programs via the Academic Task Force.

    - Provide an on-line platform within the CSLF web site to include Academic Task Force information.

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2 Baseline Survey of Mechanisms for International Collaboration and Key CCS Academic Research Groups, Summer Schools and Networks

The following provides an initial baseline survey of mechanisms for international collaboration and key CCS academic research groups, summer schools, and networks for Academic Task Force members. The Task Force will complete survey information for all CSLF member countries by the CSLF Mid-Year Meeting in 2016.

2.1 United States (Academic Task Force Co-Chair)

The U.S. Department of Energy (DOE), Office of Fossil Energy manages its CCS RD&D under the Clean Coal Research Program, which is implemented jointly by the Office of Fossil Energy and the National Energy Technology Laboratory (NETL). Both organizations engage in international collaborative activities through formal agreements and informal arrangements such as dialogues or memorandum of understandings (MOUs). NETL also conducts onsite CCS research with universities and the private sector and hosts international researchers and visiting scientists. Additionally, international collaborative activities may be conducted under other instruments such as a contract, grant or other cooperative agreements, Cooperative Research and Development Agreement (CRADA), or Work-for-Others. DOE CCS funding opportunity announcements (FOAs) require prime recipients to be incorporated in the US; however, a foreign entity may receive funding as a sub-recipient. In addition to DOE, the National Science Foundation has supported international CCS research collaborations and student exchanges under various program areas.

Key University Research Programs

2.1.1 Carnegie Mellon University, Department of Engineering and Public Policy, Energy and Environmental Systems

The Energy and Environmental Systems group at Carnegie Mellon University's (CMU) Department of Engineering and Public Policy (EPP) has pioneered the development of the Integrated Environmental Control Model (IECM), a stochastic simulation model used worldwide to design and evaluate cost-effective emission control systems for fossil-fuel power plants, including advanced processes for CCS. CMU is also a leader in the arena of CCS public policy with research on technology innovation and the relationship between regulation and technology development. CUM's EPP is also member of the CCS Regulatory Project.

Contact: Dr. Edward S. Rubin, Professor, Engineering & Public Policy, and Alumni Chair Professor, Environmental Engineering and Sciences– (412) 268-5897 or rubin@cmu.edu

2.1.2 Columbia University, Park Group

The Park Group at Columbia University's Lenfest Center for Sustainable Energy in the Earth Institute is leading a worldwide multidisciplinary CCUS Research Coordination Network (RCN) and supports the CCUS summer school, Research Experience in Carbon Sequestration (RECS). Park Group also conducts a number of research activities including: fundamental studies of novel organic-inorganic hybrid nanomaterials for application in carbon capture and conversion; tailored

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synthesis of engineered carbon-neutral filler materials; in-situ and ex-situ carbon mineralization and production of hydrogen and liquid fuels from biomass and solid municipal wastes with integrated carbon sequestration.

Contact: Dr. Ah-Hyung (Alissa) Park, Interim Director of Lenfest Center for Sustainable Energy, The Earth Institute, Columbia University and Co-Principal Investigator, Research Coordination Network on Carbon Capture, Utilization and Storage – (212) 854-8989 or ap2622@columbia.edu

2.1.3 University of Kentucky, Center for Applied Energy Research

The PowerGen Research group at the University of Kentucky's Center for Applied Energy Research (CAER) works in a number of CCS research areas including: post-combustion CO_2 capture (heat-integrated amine and ammonia scrubbing); oxyfuel combustion through chemical looping combustion for solid fuels; green power production via biomass utilization (co-firing, biomass liquefaction, and biodiesel by-product glycerine combustion); and plant performance improvement and process optimization. The University of Kentucky is also a member of the US-China Clean Energy Center.

Contact: Dr. Kunlei Liu, Associate Director for Research, CAER – (859) 257-0293 or kunlei.liu@uky.edu

2.1.4 University of North Dakota, Energy & Environmental Research Center, Center for Climate Change & Carbon Capture and Storage

The Energy & Environmental Research Center's (EERC) Center for Climate Change & Carbon Capture and Storage has two major CCS programs:

- Plains CO_2 Reduction (PCOR) Partnership: Established in 2003, PCOR is one of seven regional partnerships operating under the U.S. DOE NETL Regional Carbon Sequestration Partnership Program. PCOR is currently planning two commercial-scale CO_2 storage projects over the next few years that will inject 1 million tons of CO_2 per year.
- Partnership for CO_2 Capture (PCO_2C) Technology Development: PCO_2C is currently conducting a pilot-scale demonstration to test selected separation and capture technologies for fossil fuel- and biomass-fired systems.

Contact: John Harju, Associate Director for Research - (201) 777-5157 or jharju@undeerc.org

2.1.5 The University of Texas at Austin, Gulf Coast Carbon Center

The Gulf Coast Carbon Center (GCCC) has a portfolio of seven major field research projects focused on technologies to monitor subsurface CO_2 storage. GCCC has also led a number of projects on storage capacity estimates, EOR screening, economic assessments, leakage risks to water resources, pressure assessments, and CCUS systems integration. GCCC hosts STORE, a new training and education effort.

Contact: Dr. Susan D. Hovorka, GCCC Principal Investigator and Senior Research Scientist at The University of Texas at Austin Bureau of Economic Geology – (512) 471-4863 or susan.hovorka@beg.utexas.edu

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2.1.6 The University of Texas at Austin, Luminant Carbon Management Program

Founded in 2007, the Luminant Carbon Management Program at the Rochelle Lab offers PhD candidates at the university opportunities to conduct research on carbon capture from coal and natural gas power plants with a focus on amine scrubbing. There are currently 16 graduate students working on collecting thermodynamic and rate measurements, testing amine degradation, mitigating nitrosamines, quantifying aerosol formation, creating process models, improving process design and efficiency, and understanding pilot plant results.

Contact: Dr. Gary T. Rochelle, Carol and Henry Groppe Professor in Chemical Engineering, Department of Chemical Engineering– (512) 471-7230 or gtr@che.utexas.edu

2.1.7 Stanford University

The Global Climate & Energy Project (GCEP) develops and manages a portfolio of CCS research programs that is a part of the Carbon-Based Energy Systems research group including: carbon capture systems analysis; carbon-based sorbents for selective CO_2 capture; new materials and processes for energy-efficient carbon capture; novel ionic liquids for pre-combustion CO_2 capture, and multiphase flow of CO_2 and water in reservoir rocks. GCEP also has a number of external collaborations with leading CCS academic research groups around the world.

Contact: Dr. Sally Benson, Director, GCEP – (650) 725-0358 or smbenson@stanford.edu

The Stanford Center for Carbon Storage (SCCS) in the Department of Energy Resources Engineering focuses on CO_2 storage in saline aquifers, shale and coal formations, and mature or depleted oil and gas reservoirs and addresses critical questions related to flow physics and chemistry, simulation of the transport and fate of CO_2 in geologic media, rock physics, geophysical monitoring, and geomechanics.

Contact: Dr. Anshul Agarwal, Executive Director, SCCS, Stanford University - anshula@stanford.edu

2.1.8 West Virginia University, Energy Institute

West Virginia University's (WVU) Energy Institute coordinates University-wide energy research in engineering, science, technology and policy. It also facilitates domestic and international partnerships. Under the Energy Institute, WVU's National Research Center for Coal and Energy (NRCCE) has a broad CCUS portfolio and is a member of a number research networks including the Advanced Virtual Energy Simulation Training and Research (AVESTAR), and the Zero Emissions Research and Technology (ZERT) focusing on understanding the basic science of underground geologic CO_2 storage. The Energy Institute also leads the US-China Clean Energy Research Center's Advanced Coal Technology Consortium (CERC-ACTC) and coordinates US and China joint CCUS research with other universities including the University of Wyoming and University of Kentucky.

Contact: Dr. Brian J. Anderson, Director, Energy Institute, (304) 293-0823; Dr. Richard Bajura, Director, National Research Center for Coal and Energy, (304) 293-6034 or Richard.Bajura@mail.wvu.edu

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Summer Schools

2.1.9 Research Experience in Carbon Sequestration (RECS)

The Research Experience in Carbon Sequestration (RECS) is the premier US CCUS education and training experience and career network. Founded in 2004, with support from US DOE and recent sponsorship from the CCUS-RCN, the intensive 10-day, interactive program combines classroom instruction with group exercises, over 10 CCUS site visits including the National Carbon Capture Center and the Kemper County Energy Facility, and hands-on field activities that cover the range of CCUS science, technology, policy, and business topics. The RECS network has over 400 alumni and 100 faculty that represent the nation's leading CCUS experts. The program is held annually in June for 30 people and is open to a limited number of international participants. RECS 2016 will be hosted by Southern Company in Birmingham, AL.

Contact: Pamela Tomski, Founder & Director, RECS – (202) 390-8896 or ptomski@mac.com

Research Networks

2.1.10 Research Coordination Network on Carbon Capture, Utilization and Storage

The Research Coordination Network on Carbon Capture, Utilization and Storage (RCN-CCUS) facilitates interdisciplinary research collaborations and training to develop new understanding, theories, models, technologies, and assessment tools for the CCUS field. Participating members include researchers in academia, national labs, young professionals, K-12 teachers, international partners and industrial members as well as the five Engineering Founder Societies (American Institute of Chemical Engineers, American Institute of Mining, Metallurgical, and Petroleum Engineers, American Society of Civil Engineers, American Society of Mechanical Engineers and the Institute of Electrical and Electronics Engineers).

Contact: Dr. Ah-Hyung (Alissa) Park, Columbia University – (212) 854-8989 or ap2622@columbia.edu; Dr. Darlene Schuster, Executive Director, Institute for Sustainability (an AIChE Technological Community) (410) 458-5870 or darls@aiche.org

2.1.11 Zero Emissions Research and Technology

The Zero Emission Research and Technology Center (ZERT) is a research collaborative led by Montana State University focused on understanding the basic science of underground (geologic) CO_2 storage and to develop technologies that can ensure the safety and reliability of that storage. ZERT is a partnership involving DOE laboratories (Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, National Energy Technology Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory) as well as universities (Montana State University and West Virginia University)

Contact: Dr. Lee Spangler, ZERT Project Director, Montana State University – (406) 994-2891 or spangler@montana.edu

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International Student Internships and Exchanges

2.1.12 US Department of Energy, Office of Fossil Energy

With funding support from partner countries, the US DOE, Office of Fossil Energy hosts international student interns that allow international participants to be stationed at DOE Headquarters in Washington, DC for a 6-8 week term. The internships are not conducted under a formalized DOE program rather they are partnerships with international groups who fund the position. The DOE offers a focus on various aspects of fossil energy scientific, technical and policy issues, including CCUS.

2.2 Mexico (Academic Task Force Co-Chair)

Since 2008, Mexico has undertaken a number of measures to develop and implement CCUS technologies. The Ministry of Energy of Mexico (SENER), Clean Technologies Direction manages CCUS activities throughout the country, which is guided by the CCUS Technology Roadmap in Mexico. The Ministry of Environment and Natural Resources (SEMARNAT) is also engaged in CCUS. As part of SENER, the Sustainable Energy Fund supports national academic research and collaborations with stakeholders in Mexico. Other developments include the creation of a Mexico CCUS Center supported by The World Bank CCS Trust Fund and development of a CCUS Masters degree specialization at the National Autonomous University of Mexico (UNAM) under a collaboration with Lawrence Berkley National Laboratory. The World Bank CCS Trust Fund is also supporting a number of enabling activities to advance Mexico's CCUS roadmap including legal, regulatory and public engagement frameworks. Mexico has undertaken a number of capacity development activities over the last few years to enhance understanding of CCUS, particular among the academic community. The Global CCS Institute, in partnership with SENER and with support from Asia Pacific Economic Cooperation (APEC), led these activities.

2.3 Canada (Academic Task Force Member)

Governments in Canada fund CCS RD&D through a range of programs delivered by federal funding providers such as Natural Resources Canada (NRCan), Sustainable Development Technology Canada, and the National Research Council Canada, as well as through provincial programs, mainly in Alberta and Saskatchewan. Also, the Natural Sciences and Engineering Research Council of Canada provides grants specifically for university-based research in the natural sciences and in engineering, which includes grants for academic CCS research. NRCan's Canmet ENERGY-Ottawa, one of Canada's national energy laboratories, conducts onsite CCS research in collaboration with universities and the private sector and hosts international researchers and visiting scientists, and facilitates NRCan scientists' visits to research facilities abroad. NRCan also engages in international collaborative activities in CCS through arrangements such as dialogues or MOUs.

Key University Research Programs

2.3.1 University of Calgary

The University of Calgary's CREATE Training Program in Carbon Capture provided a comprehensive training opportunity for students working on carbon capture technology. Working in coalition with energy research partners, the program trains students to develop various carbon capture technologies in every stage in the development of new carbon capture technologies across several themes, including

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pre-combustion capture, post combustion capture and biological capture. Researchers are being funded at the universities of Calgary, Alberta, Ottawa, Carleton and British Columbia, with additional collaborators from Canada and around the world, including Cranfield University in the UK, CanmetENERGY Natural Resources Canada, and the Canadian Clean Power Coalition.

Contact: George Shimizu- (403) 220-5347, gshimizu@ucalgary.ca

At the University of Calgary's Schulich School of Engineering, Chemical and Petroleum Engineering, the Energy Innovations for Today and Tomorrow research group is collaborating with industry to explore conventional and unconventional energy resources from the Arctic to the deep biosphere to find more efficient extraction methods as well as finding new resources, such as gas hydrates. They are making breakthroughs in renewable and alternative energy including solar energy conversion, fuel cells, and hydrogen and CO_2 capture and storage. Research activities include fluid flow and transport phenomena in porous media, CO_2 storage in geological media, and upscaling and parameter estimation.

Contact: Hassan Hassanzadeh, (403) 210-6645, hhassanz@ucalgary.ca

Researchers at the University of Calgary's Gas Hydrates Laboratory study gas hydrate thermodynamic properties and formation and decomposition kinetics using particle size analyzers. They develop numerical models to evaluate the viability of using hydrate to sequester CO_2 and the potential of natural gas production from hydrates.

2.3.2 University of Alberta, Department of Civil and Environmental Engineering, School of Mining and Petroleum Engineering, Geotechnical Engineering

The research team at the University of Alberta's Geomechanical Reservoir Experimental Facility conducts research on resource recovery in unconventional hydrocarbon reservoirs and focuses on reservoir geomechanical behavior and its impact on resource recovery and operational risk. The team also investigates the utilization and storage of CO_2 with a focus on improving reservoir geomechanical understanding of the relationships between measured and modeled subsurface fluid flows spanning the range of spatial and temporal scales relevant to economic and environmentally sustainable resource management.

Contact: Rick Chalaturnyk- (780) 492 9992, rjchalaturnyk@ualberta.ca

2.3.3 Carleton University, Carleton Sustainable Energy Research Centre

The Carleton Sustainable Energy Research Centre (CSERC) conducts research in both engineering and policy related to the energy system (energy production, transportation and end-use) as well as all of the connections and outlining policies that encompass these three broad categories. Research under the Implementing Sustainable Energy Technology heading includes Carbon Capture and Storage, which looks at the issues that decision-makers confront in encouraging the uptake of this technology and how to manage uncertainties and regulate risks.

Contact: James Meadowcroft- (613) 520-2600 x 2214, james_meadowcroft@carleton.ca

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2.3.4 University of British Columbia

The University's of British Columbia's Department of Chemical and Biological Engineering conducts a wide range of energy research including carbon dioxide capture and removal, and waste water treatment, energy efficiency and analysis.

Contact: Peter Englezos, peter.englezos@ubc.ca

In the Department of Earth, Ocean and Atmospheric Science, the Global Environmental Change research group is focused on identifying and evaluating novel CO_2 storage pathways, selective adsorption of CO_2 and methane in coal seams, and approaches to accelerating carbonation reactions in mine residue.

Contact: Gregory Dipple, (604) 827-0653, gdipple@eos.ubc.ca

2.3.5 University of Regina

Dr. Yongan Gu's research group in the Faculty of Engineering and Applied Science, Petroleum Systems Engineering has four primary research areas: CO_2 EOR, solvent vapour extraction (VAPEX), asphaltene precipitation and deposition, and fluid phase behaviour and PVT studies. One of the groups major research interest CSS in depleted oil and gas reservoirs and saline aquifers.

Contact: Yongan (Peter) Gu, (306) 585-4630, peter.gu@uregina.ca

The Clean Energy Technologies Research Institute (CETRi) of the University of Regina is a research and demonstration institute that integrates clean energy and CO_2 capture research and undertakes broader thematic research to address challenges related to GHG mitigation and the development of alternative clean energy technologies. CETRi actively researches and demonstrates the possibilities of drastic improvements in CCCS technologies, as well as methods for minimizing the costs associated with these technologies.

Contact: Raphael Idem (Director), (306) 585-4470, raphael.idem@uregina.ca

Research Networks

2.3.6 CMC Research Institutes

CMC Research Institutes, hosted at the University of Calgary, is a neutral, independent, not-for-profit organization dedicated to accelerating innovation associated with addressing the challenge of industrial GHGs. CMC committed CAN$22 million to 44 research projects in Canadian universities. This investment led to additional contributions and partners from more than 100 companies, stakeholder organizations and international universities. CMC is now building on this network of global researchers to engage with projects ready for field and pilot testing. CMC's Carbon Capture and Conversion Institute (CMC.CCCI), a collaboration with the University of British Columbia's Department of Chemical and Biological Engineering and its affiliated Clean Energy Research Centre, and BC Research Inc., accelerates the development, piloting, scale-up and validation of new carbon capture and conversion technologies. CMC's Containment and Monitoring Institute (CMC.CaMI), an affiliation between CMC and the University of Calgary, is focused on the detection and monitoring of subsurface fluids, including CO2. A key part of CMC.CaMI is its Field Research Station, which offers clients the opportunity to test and refine measurement, monitoring and verification technologies for subsurface storage of liquids, including CO2.

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Richard Adamson, President, CMC Research Institutes- 403-210-7767, richard.adamson@cmcghg.com

2.4 Poland (Academic Task Force Member)

Over the past decade, Poland has been engaged with CCS research, development and demonstration as well as regulatory framework developments. In 2008, the Polish Ministry of Environment launched the National Programme, *Actions of the Ministry of Environment for assessment of formations and structures suitable for underground CO_2 geological storage*. In the same year, the Ministry of Economy initiated the Demo Clean Coal Program for Energy, which includes CCS and runs through 2015. CCS is also included under the Ministry of Science's Strategic R&D Program under Advanced Technologies for Energy Generation. Poland's academic CCS R&D is funded from both the Ministry of Environment and the Ministry of Science and Higher Education. The EU Framework Programme and the Government of Norway through the Polish-Norwegian Research Programme also support CCS academic research in Poland.

Key University Research Programs

2.4.1 AGH University of Science and Technology

AGH University of Science and Technology is one of the leading institutes of technology and the largest technical university in Poland. CCS research focuses on geological carbon storage.

Contact: Dr. Stanislaw Nagy, Professor of Thermodynamics and Natural Gas Engineering, AGH University of Science and Technology

2.4.2 Częstochowa University of Technology

Częstochowa University of Technology is the largest and oldest institution of higher education in Częstochowa, Poland. Current CCS research includes: economically efficient and socially acceptable CCS/EOR processes, and innovative idea for combustion of solid fuels via chemical looping technology. In 2015, the university was a main organizer of the 1st International Conference & CCS Summer School that focused on advanced CO_2 capture technologies.

2.4.3 Silesian University of Technology, Institute of Thermal Technology

The Silesian University of Technology (SUT) is one of Poland's largest technical universities and most of its CCS research is based out of the Institute of Thermal Technology (ITT). With strong links to Polish industry and local government, ITT focuses on energy systems analysis and has decades experience on clean coal technologies, including oxy-fuel combustion. ITT is a member of Optimisation of Oxygen-based CFBC Technology with CO_2 Capture (O2GEN), a European consortium that researches and demonstrates second generation oxyfuel combustion, and works on heat integration and plant optimization to minimize the energy penalty associated with CO_2 capture. ITT also has a current research project on economically efficient and socially accepted CCS-EOR processes.

Contact: Dr. Marcin Liszka, Faculty of Power and Environmental Engineering, Institute of Thermal Technology, marcin.liszka@polsl.pl

International Student Internships and Exchanges

2.4.4 Krajowa Szkoła Administracji Publicznej (KSAP) / National School of Public Administration

Poland's National School of Public Administration trains students who after graduation take up positions in the central administration and may enter the Civil Service Corps or current Civil Service employees and Civil Servants who require continuing training. KASP graduates work at all levels of the Polish public administration in Poland and abroad. KASP funds an internship program with the US Department of Energy (DOE) for Polish student or Civil Servant to be stationed at DOE Headquarters in Washington, DC for a 6-8 week term. The internship with DOE offers a focus on various aspects of fossil energy scientific, technical and policy issues, including CCUS.

2.5 Saudi Arabia (Academic Task Force Member)

Current CCS activities in Saudi Arabia are primarily focused on basic technical and policy research.

2.5.1 King Abdulaziz City for Science and Technology (KACST)

This initiative has funds allocated for supporting research on CCS through the KACST TIC on CCS (which is established in KFUPM). As well, KACST provides support of projects on CCS through the National Science, Technology and Innovation Program.

2.5.2 King Fahd University of Petroleum & Minerals (KFUPM)

The Technology Innovation Center for CCS at KFUPM received funding of US$2.7 per year for a five-year period (2011-2015) with a research focus on oxy-fuel combustion, mobile capture, site assessments and monitoring, measurement and verification of CO_2 storage. Activities include new technology R&D and technology transfer, as well as training and education of both graduate and undergraduate students in the area of CCS. The Center also conducts conferences, symposia, and seminars, as well as offering short courses.

2.5.3 King Abdullah University of Science and Technology (KAUST)

The Clean Combustion Research Center, which is working toward a knowledge-based understanding of combustion phenomena, is establishing a graduate-level research program for the education and training of future experts in the area of clean combustion technology (including CCS).

2.5.4 Saudi Aramco, and King Abdullah Petroleum Studies and Research Center (KAPSARC)

Ongoing energy and environmental research at KAPSARC includes the development of an overall framework for a nationwide CCS program in the Kingdom of Saudi Arabia. This will include assessing the status of all ongoing CCS activities and programs and developing the proposed framework for CCS.

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2.6 South Africa (Academic Task Force Member)

Research Networks

2.6.1 South African Centre for Carbon Capture and Storage

The South African Centre for Carbon Capture and Storage (SACCCS), established in 2009 as a division of the South African National Energy Development Institute (SANEDI), leads CCS activities in South Africa. The SACCCS undertakes CCS R&D and capacity building (both human and technical). The SACCCS is financially supported by the South African Government through SANEDI, the governments of Norway and South African industries, Sasol and Eskom. Current additional participants are the Anglo American, Xstrata Coal, Total, PetroSA, Agence Francaise de Developpement (AFD), Alstom, and Exxaro. Very few academic institutions are engaged in CCS research and SACCCS would like to see more attention and funding support to be given to increasing academic studies and research. In order to address these needs the Centre is supporting bursaries, student projects and is planning to support school projects. One project supported a scoping study on CO2 mineralization by Dr. Frederic Doucet (CGS)

2.7 United Kingdom (Academic Task Force Member)

The UK has a four-year (2011-2015) £125 million cross-government CCS research, development and innovation programme. Funding comes from the Department of Energy and Climate Change (DECC), the Technology Strategy Board (TSB), the Energy Technologies Institute (ETI) and the Research Councils. It covers:

- £62million to support fundamental research and understanding
- £28million to support the development and demonstration of CCS components and next generation technologies (such as turbines or new solvents to capture the carbon dioxide)
- £35million for pilot scale projects to bridge the gap between research and commercial scale deployment

In total, over 100 separate projects are being funded through this programme.

Additionally, £2.5m has been made available to develop North Sea CO_2 storage. This new funding from DECC's Innovation Fund, will be delivered by the Energy Technologies Institute (ETI).

Key University Research Programs

2.7.1 Imperial College London, Centre for Carbon Capture and Storage

The Imperial College Centre for Carbon Capture and Storage (IC4S), with links to the college's Energy Futures Laboratory and the Grantham Institute for Climate Change, researches all aspects of the CCS chain with an overarching systems approach that also includes analysis of legal and regulatory issues. Primary research areas include: solvent based capture; solid looping; oxyfuel; IGCC / hydrogen combustion; CO_2 reforming; carbon fuel cells; systems; power plant modelling and integration; CO_2 storage; policy and legal. (Contacts for researchers in for these areas, and more detail on their research, may be found here.)

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Contact: Dr. Paul Fennell, Faculty of Engineering, Department of Chemical Engineering, Imperial College - +44 (0)20 7594 6637 or p.fennell@imperial.ac.uk

2.7.2 Scottish Carbon Capture & Storage

Founded in 2005, Scottish Carbon Capture & Storage (SCCS) is the UK's largest CCS research group and is a partnership of the British Geological Survey, University of Edinburgh and Heriot-Watt University working together with universities across Scotland. SCCS is funded by the Scottish Funding Council (SFC) and the Energy Technology Partnership (ETP) and works across all aspects of CCS from capture engineering and geoscience, to social perceptions and environmental impact, to law and petroleum economics. SCCS undertakes fundamental research and is available for consultancy. SCCS maintains a broad expertise and large portfolio of research projects across the CCS chain.

Contact: Various SCCS team members should be contacted based on area of interest.

2.7.3 University of Edinburgh, School of Engineering

The carbon capture group at the University of Edinburgh's School of Engineering is one of the largest in the UK that is involved in a large portfolio of projects with funding from the UK and a number of international partners. Their two main fields of interest include adsorption and power plant engineering. The adsorption group's expertise covers: testing and ranking adsorbents for CO_2 capture using the zero-length column system; molecular modeling and simulation of novel nanoporous materials; dynamic process modeling and simulation of adsorption and membrane-based capture technologies; process integration and optimization; circulating fluidized beds and mixed-matrix membranes and carbon nanotubes. The power plant engineering group's expertise includes: power plant engineering with carbon capture; post-combustion capture for coal and natural gas, and oxyfuel combustion; process engineering, control and techno-economics of transient capture operations, and techno-economics of CO_2 capture and transport in low carbon electricity markets. The group, along with the University of Edinburgh's Schools of Geosciences, Engineering, and Chemistry, is also a member of the Scottish Carbon Capture and Storage (SCCS) Centre, the largest CCS grouping in the UK. The University of Edinburgh also offers a Masters program in CCS that is run in conjunction with the School of Engineering and School of Geosciences.

Contact: Dr. Jon Gibbins, Director & Principal Investigator, UKCCSRC and Professor of Power Plant Engineering and Carbon Capture, University of Edinburgh- +44(0) 131 650 4867, jon.gibbins@ed.ac.uk

Research Networks

2.7.4 The UK CCS Research Centre, University of Edinburgh

The UK CCS Research Centre (UKCCSRC) is a virtual network that coordinates all CCS academic research supported by the UK government, brining together over 250 academics. The UKCCSRC is supported by the Engineering and Physical Sciences Research Council (EPSRC) as part of the Research Councils UK Energy Programme, with additional funding from the Department of Energy and Climate Change (DECC).

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Contact: Dr. Jon Gibbins, Director & Principal Investigator, UKCCSRC and Professor of Power Plant Engineering and Carbon Capture, University of Edinburgh- +44(0) 131 650 4867, jon.gibbins@ed.ac.uk

2.8 IEAGHG Programme

Summer Schools

2.8.1 IEAGHG CCS Summer School

Established in 2009, the IEAGHG CCS Summer School is a one-week program that takes place in different countries around the world each year and includes presentations and discussion groups led by international CCS experts. In addition to the discussion programme, the students are divided into teams to undertake short research activities on issues of importance within the CCS area, with a presentation to their peers at the end of the week. Time is also allocated for networking and for informal discussions with the assembled experts. The program targets young scientists, e.g. PhD students with a background in engineering, geo-technologies, socio-economics. Generally some 60 students from both developed and developing countries participate in each programme. Over 20 experts from industry and research conduct lectures and lead discussion groups on various CCS topics.

Contact: Tim Dixon, tim.dixon@ieaghg.org

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3 Leveraging Opportunities

3.1 CSLF Capacity Development Fund

The CSLF Capacity Building Fund was established in 2009 with funding from Australia, Canada, Norway and the United Kingdom to provide capacity building support to emerging economy CSLF members through projects such as workshops, study tours, technical training, and commissioned studies. The Fund's Governing Council has, to date, targeted Brazil, China, India, Mexico and South Africa for funding opportunities. All CSLF countries are eligible to apply for funding; however, the expectation is that the distribution of funding should focus on emerging economy members and represent a wide geographical spread. The following are examples of the types of capacity development activities the Fund has supported:

- workshops, presentations and seminars;
- site visits and study tours;
- practical training such as customised programs, site placements and secondments;
- roadmaps and analysis of issues;
- coaching and mentoring;
- establishing and facilitating networks between people, groups and organisations;
- education in the form of external or online courses, integration into university curriculums and research grants.

In 2015 the Governing Council approved the five projects in Brazil, China, India and Mexico and is currently accepting new project proposals.

Contact: Alice Gibson, Global CCS Institute, Alice.Gibson@globalccsinstitute.com

3.2 World Bank CCS Trust Fund

In November 2009, the World Bank CCS Trust Fund was established with contributions from the Government of Norway and the Global CCS Institute. The Norwegian Government has since provided two further contributions to the Fund along with the Government of the United Kingdom. The Fund supports early stage CCS activities such as legal and regulatory framework development, storage capacity assessments, and analysis of key issues and barriers. The Fund is moving towards support for pilot projects in developing countries with primary activity in China, South Africa and Mexico.

3.3 Asian Development Bank CCS Trust Fund

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4 CSLF Academic Task Force Participants

United States (Co-Chair)

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-P-2015-08
19 October 2015

POLICY GROUP

Accelerating the Adoption of 2nd and 3rd Generation Carbon Capture Technologies

Background

At the November 2013 CSLF Ministerial Meeting in Washington D.C., the Exploratory Committee of the CSLF 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. "

Accordingly, 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 was formed to:

- Identify emerging 2nd and 3rd generation emerging technologies for CO_2 capture and testing facilities;
- Assess associated enabling mechanisms at a high level; and
- Propose potential areas of follow-up for the CSLF to facilitate the acceleration of 2nd and 3rd generation carbon capture technologies.

The following executive summary is based on the research carried out by Norway and Canada.

Action Requested

The Policy Group is requested to review the Task Force executive summary document.

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Executive Summary - Accelerating the Adoption of 2nd and 3rd Generation Carbon Capture Technologies

Background

At the November 2013 CSLF Ministerial Meeting in Washington D.C., the Exploratory Committee of the CSLF 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. "

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- Identify emerging 2nd and 3rd generation emerging technologies for CO_2 capture and testing facilities;
- Assess associated enabling mechanisms at a high level; and
- Propose potential areas of follow-up for the CSLF to facilitate the acceleration of 2nd and 3rd generation carbon capture technologies.

The following executive summary is based on the research carried out by Norway and Canada.

What are 2nd and 3rd Generation 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*** include technology components that are in the early stage of development or are conceptual. They have the potential for performance and cost improvements beyond those expected from 2nd generation technologies and are expected for demonstration in the 2030–2035 time period.

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

Section I – Technical Overview

The report describes efforts to identify emerging technologies 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 in the order of 100 tonnes per day and more.

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The study is based on a literature and web review of the status of emerging technologies and existing test facilities. It was performed jointly by the CSLF Policy and Technical Groups. Neither the inventory of emerging technologies nor of test facilities can be regarded as complete.

Approximately 30 groupings of emerging technologies have been identified. Most are 3rd generation, i.e. Technology Readiness Level (TRL) 1 – 3(4) and must be classified as tested at laboratory or bench scale only. A minority is classified as 2nd generation, i.e. TRL 4(5) – 6. 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. Also note that the potential for cost reduction usually refers to reduction of Levelized Cost of Electricity (LCOE) but for some higher rates of potential cost reduction, it may only refer to cost reduction of the capture component only.

?=Uncertain estimates that are not quoted

Table 1A. Post-combustion capture technologies

Technology	Generation/ TRL	Potential for energy savings	Potential for cost reduction	Applications
Precipitating solvents	2nd-3rd/4-6	10-20% rel. MEA (2.3-3.6 GJ/t CO_2)	5-10%	Power, steel, cement
Two-phase liquid system	2nd-3rd/4-5	2.0-2.3 GJ/t CO_2	5-10%	Power, steel, cement
Enzymes	3rd/1-2(3)	30-35% rel. MEA (?)	5-10	Power, steel, cement
Ionic fluids	2nd-(3rd)/1 – 4	15 -20 % rel. MEA	?	Power, steel, cement
Encapsulated solvents	3rd/1-2	?	?	Power, cement
Electrochemical solvents	3rd/1-2	Uncertain	Uncertain, may be none	Power, cement, steel, aluminum
Calcium looping system	2nd/5-6	Coal: Efficiency penalties 5-10% Gas: no benefits	May be significant	Power, cement
Other looping systems	3rd/1-2	?	?	Power, steel, cement
Vacuum Pressure Swing (VPS)	3rd/2-3	Uncertain, could be good	May be not	Power, cement
Temperature swing (TS)	3rd/1-2	Uncertain, appears limited	?	Power, cement
Polymeric membranes	2nd/5-6	Fuel consumption: 50% down rel. MEA?	30%	Power, cement, steel
Polymeric w/cryogenic	2nd/2-6	Better than above	30%	Power, cement, steel
Cryogenic (low temp)	2nd-3rd/3-5	Competitive MEA	Moderate ?	Power
Supersonic	3rd/1-2	?	?	Power

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Table 1A (cont.). Post-combustion capture technologies

Technology	Generation/TRL	Potential for energy savings	Potential for cost reduction	Applications
Hydrates	**3^{rd}/1-3**	**?**	**?**	**Power**
Algae	3^{rd}/1-3	?	?	Power and most other industries
CO_2-enriched flue gas	2^{nd}/5-6	?	?	Power
Pressurized post-combustion	2^{nd}-3^{rd}/2-5	?	?	Power

Table 1B Pre-combustion capture technologies

Technology	Generation/TRL	Potential for energy savings	Potential for cost reduction	Applications
Sorption Enhanced Water Gas Shift (SEWGS)	2^{nd}/4-5	Efficiency gain 3-4 %-points	May be up to 30%	Power, refinery, H_2 production
Sorption Enhanced Steam-Methane reforming (SE-SMR)	3^{rd}/1-2	Appears limited in NGCC	?	Power, refinery, H_2 production
Metal and composite membranes	2^{nd}-3^{rd}/3-5	Efficiency gain 3 %-points	May be up to 25-30% (?)	Power, refinery, H_2 production
Ceramic membranes	2^{nd}-3^{rd}/2-4	As above?	May be up to 25% (?)	Power, refinery, H_2 production
Cryogenic (low temperature)	3^{rd}/1-3	Efficiency gain 3-4 %-points; 1 GJ/t CO_2	30 – 50% (last w/ recycle of CO_2)	Power, refinery, H_2 production
Concepts with fuel cells	2^{nd}-3^{rd}/3-6	Efficiency gain up to 30 %-points rel. IGCC and gas w/MEA	> 70%	Coal and biomass power, refinery, H_2 production

Table 1C Oxy-combustion capture technologies

Technology	Generation/TRL	Potential for energy savings	Potential for cost reduction	Applications
Chemical looping combustion	3^{rd}/2-3	Efficiency gain 2-4 %-points (?)	Large	Coal power
Oxygen transporting membranes (OTM) power cycle	3^{rd}/2-3	Efficiency gain 5 %-points over NCCC w/MEA(?)	?	Power
Pressurized oxy-combustion	3^{rd}/2-4	~35- 40% - efficiency	reduction 22 – 32+%, on power, depending on cycle	Coal and biomass power

The potential for cost end energy consumption reductions vary from very small to significant in the above table. However, it is important to note that the numbers are based on a literature survey and may not be derived in a consistent manner. Furthermore, the technologies are at different levels of maturity, which will influence the uncertainties of the estimates. Factors that contribute to the uncertainties include:

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- Comparison to different baselines (old, new, unfavourable, etc in addition to different assumptions and battery limits)
- Cost unit (e.g. cost of electricity (COE), levelised cost of electricity (LCOE), cost per tonne CO_2 captured or abated
- First of a kind (FOAK) or nth of a kind (NOAK)
- Basically unfamiliar production methods and materials
- Reporting in efficiency changes (% relative some baseline) or energy requirements (GJ/tonne CO_2)
- Electricity vs. thermal energy
- Work vs. thermal energy
- Limited information and testing of emerging technologies.

It is important to be conscious of these uncertainties when choosing technologies for further development and testing.

The study has identified 11 test facilities for CO_2 capture technologies that are or will be independent of technology providers and that may be used to speed up the development of emerging capture technologies. Only two of these are sufficiently large to allow the next step in the technology development to be full scale. The others must be classified as small scale testing capabilities, i.e. < 10 000 tonnes CO_2/year or the equivalent of 2 MW coal fired power. These are often run on simulated flue gas. Testing at these smaller facilities will require at least one intermediate step before going to full scale. The majority of the identified test facilities are designed for post-combustion capture of CO_2.

There also several test or demonstration facilities for CO_2 capture technologies that are owned by technology providers to test specific proprietary technologies. These are in general not available for testing of other technologies. Some of these facilities are briefly described in the report.

The study revealed that the literature uses a range of definitions for technology maturity and test scales and sometimes inconsistent use of terms. For example, although it is difficult to avoid a gliding scale between the terms “pilot” and “demonstration” size facilities, a difference in terms of captured CO_2 has been found to vary with almost 3 orders of magnitude and at least one order in terms of power.

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Section II – Mechanisms Overview

a) Research Approach

- Over 35 individuals were interviewed from about 30 organizations in 8 CSLF countries and the EU, as follows:
    - **Government**: Alberta, EC, Norway, The Netherlands, UK, US
    - **Research Programs, Centres & Networks**: Carbon Management Canada, CanmetENERGY-Ottawa, RITE (Japan), Korea Institute of Energy Research, Research Council of Norway, CATO2 (The Netherlands), Energy Technologies Institute (UK), GassNova
    - **Researchers**: UBC, UCalgary, Tsinghua University (China)
    - **Test Centres**: NCCC (US), SaskPower, GassNova (TCM)
    - **Technology Developers**: CO2 Solutions, Cansolv, Carbon Clean Solutions, Linde
    - **Industry Associations**: Canadian Clean Power Coalition, Canadian Oil Sands Innovation Alliance, The Carbon Capture & Storage Association (UK)
    - **Customers/Commercial Facilities**: Husky Energy, Shell Global, KEPCO (Korea), SaskPower, Southern Company (for NCCC)
    - **International Organizations**: IEA, IEAGHG

- Interviewees shared their perspectives with respect to 2nd and 3rd carbon capture technologies, identifying:
    - Key barriers
    - Existing Mechanisms that work to accelerate these technologies
    - Insights on success factors / areas for improvement for existing mechanisms
    - Mechanisms that should be top priorities for policy makers

b) Overall Findings

The interviews confirmed that a variety of existing mechanisms are in use across jurisdictions[1]. Further, based on the feedback received, certain mechanisms are seen as higher priority (identified below) to drive investment in research, development, and deployment of 2nd and 3rd generation carbon capture technologies.

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[1] The research did not attempt to create a complete compendium of relevant global vehicles, mechanisms, and approaches. The examples provided are illustrative, rather than exhaustive, and emphasize the most well-known applications of each mechanism.

Mechanism	Application Examples	Stakeholder Priority
Carbon Pricing	Carbon pricing: Norway, the Netherlands, British Columbia, UK Cap and trade: EU ETS, South Korea, WCI, RGGI Hybrid: Alberta	Highest
Government Funding, National Research Funding Programs, Centers, and Networks	US, Norway, the Netherlands, Australia, UK, Canada, China, European Union, South Korea, Japan	High
Tax Incentives for R&D	U.S. (federal and state), Canada (federal and provincial), Australia	High
Operational Support	UK, U.S., Alberta, Saskatchewan	High
Carbon Capture Test Facilities	U.S., Norway, UK, Canada, etc.	High
Cooperation and Knowledge Sharing	**Bilateral:** Many, such as the U.S.-Canada Clean Energy Dialogue **Multilateral:** CSLF, IEA GHG R&D Program, Global CCS Institute	High
Loans and Loan Guarantees	U.S., Green Investment Bank (UK), European Investment Bank	Supportive
Business Development Programs	Many, including Australia, U.S., UK, Canada, Norway	Supportive
Performance Standards and Deployment Targets	**Performance standards**: Canada, UK, U.S. (proposed) **Portfolio standards:** Utah, Illinois	Moderate
Industrial CCS Hubs and Clusters	UK, the Netherlands	Moderate

A variety of common themes for advancing 2nd and 3rd generation carbon capture technologies related to barriers, enabling conditions, and key mechanisms also emerged from the research and interviews, including:

- The **barriers currently impeding 2nd and 3rd generation carbon capture technology RD&D fall into five main categories**: cost, lack of a market, technical and operational challenges, insufficient test sites in key geographies and sectors, and CO_2 storage availability and enabling regulations.
- **Preconditions for Success** include public confidence in CCS and ensuring that the current suite of large-scale CCS demonstration projects utilizing 1st generation carbon capture technologies achieves commercial deployment.

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- 1st Generation CCS Knowledge offers tremendous value to emerging technology developers making **knowledge sharing and cooperation programs** a priority for accelerating progress
- **Government Funding Programs** are generally highly regarded by both carbon capture technology developers and commercial facilities implementing carbon capture projects, have been an essential driver of progress to date, and should strive to be consistent, predictable, and include appropriate criteria and requirements for CCS.
- **Test centers / test facilities** were identified as essential by many stakeholders as they enable technology developers to test under real-world conditions with significantly lower costs and lead time and are required to prove performance across different scales, sectors, and countries (with unique flue gases).
- **Operational Support Programs** reduce operational risks and improve the business case for CCS projects by providing support with ongoing operating costs (i.e. offtake arrangements (feed-in tariffs), programs that guarantee a market for some or all output, and activity-based tax credits).
- **Tax Incentives for Research and Development** which include tax credits for R&D spending and accelerated depreciation of capital investments which a number of stakeholders, particularly technology developers, reported have been and would continue to be very beneficial.

Potential Areas of CSLF Follow-Up

Given the priorities that emerged from the research findings, and in light of the capacity of the CSLF, opportunities to enhance collective efforts to accelerate the development of emerging carbon capture technologies among governments, technology developers, technology adopters, and academia / researchers could include:

- Building on the work of the CSLF Technical Group, maintain a global inventory of test facilities' availabilities, capacities, and capabilities (different sizes, scales, fuels). This will help connect emerging technology developers to testing opportunities:
  - The inventory should include test facilities at scales as small as 1 tonne CO_2/day, to enable emerging technologies to get started and progress along a pathway toward commercialization, including progression toward larger scales of testing;
- Based on the successful model of the International CCS Test Centre Network[2] (ITCN) and the European network ECCSEL[3], CSLF should encourage and facilitate enhancing the network to cover additional regions, sectors, and levels of scale. This would help to lay the ground to accelerate the development and testing of technologies in

[2] ITCN, the International CCS Test Centre Network, is fostering knowledge-sharing among carbon capture test facilities around the world to accelerate the commercialization of technology. Its membership includes test facilities in Canada, Germany, Norway, the UK, and the U.S.

[3] ECCSEL, the European Carbon Dioxide Capture and Storage Laboratory Infrastructure, is opening access for researchers to a top quality European research infrastructure devoted to 2nd and 3rd generation CCS technologies, through a consortium of selected Centres of Excellence on CCS research from 9 countries across Europe.

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additional environments and facility configurations / conditions. As well, with increased membership, costs can be spread across a larger number of participants;

- In view of the success of the EU twinning[4] approach, assess similar cooperative opportunities among other CSLF member countries to enhance the global knowledge base and cooperation in 2nd and 3rd generation carbon capture technologies, such as:
  - Promoting cooperation between and technology testing at small, large, and similar sized facilities, with differing capabilities. This would increase the range of test opportunities and facilitate and accelerate knowledge sharing and exchange among member countries, between two or more test facilities.
  - Building a network around "families" of cooperative (twinning) projects;
- Encourage sharing of best practices in funding emerging carbon capture technologies, with the potential of documenting best practices in developing priority funding areas;
- Contribute to derivation of a consistent terminology for new CO_2 capture technologies, maturity (2nd and 3rd generation vs. emerging or transformational; consistent use of Technology readiness level, TRL) and for different testing scales (bench, lab, pilot, demonstration);
- Support efforts being made by ISO, the CCS Test centre Network and others to derive consistent performance evaluation methods and indicators;
- Enhance opportunities for researchers and developers to participate in extended visits and staff exchanges to other demonstration projects and test centres (6 months or more) as well as training opportunities, much along the lines of the European initiative ECCSEL. This item should be coordinated with the re-established CSLF Academic Community Task Force; and
- Implement mechanisms that allow developers of emerging technologies and operators of test facilities to cooperate in mutual beneficial and cost effective ways, e.g. help establishing bi- and/or multi-lateral agreements and funding mechanisms that allow emerging technologies to be tested at another nation's facilities. The ITCN and ECCSEL initiatives are examples of how governments cooperate to increase testing capacities.

[4] The EU twinning approach fosters bilateral cooperation between next generation carbon capture R&D projects. It has been implemented through a European Commission (EC) call for twinning between EC-funded and Australian projects, and will be repeated with South Korea.

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CSLF-P-2015-09
20 October 2015

POLICY GROUP

Election of Policy Group Chair

Background

As stated in Section 3.3 (a) of the CSLF Terms of Reference and Procedures, CSLF Chairs and Vice Chairs will be elected every three years. The previous election of the Policy Group Chair was at the Perth meeting in October 2012, so the next election has been scheduled for the November 2015 CSLF Ministerial Meeting in Riyadh, Saudi Arabia.

Action Requested

The Policy Group is requested to hold an election to select a Chair whose term will run through November 2018.

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Election of Policy Group Chair, Technical Group Chair, and Technical Group Vice Chairs

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

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

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

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

On 04 August 2015, the Secretariat sent an e-mail to CSLF Policy Group delegates, informing them of the upcoming election of the Policy Group Chair, the Technical Group Chair, and the Technical Group Vice Chairs, and that nominations must be received by the Secretariat no later than six weeks prior to the meeting (i.e., by 21 September 2015).

The following nominations were received by the Secretariat:

<u>Policy Group</u>

- United States has been nominated for Policy Group Chair by Canada, China, the European Commission, Italy, Norway, and Russia.

<u>Technical Group</u>

- Norway has been nominated for Technical Group Chair by China, the European Commission, Italy, Russia, and the United States.

- Australia has been nominated for Technical Group Vice Chair by China, Italy, and the European Commission.
- Canada has been nominated for Technical Group Vice Chair by the European Commission, Italy, and the United States.
- Japan has been nominated for Technical Group Vice Chair by the United States.
- South Africa has been nominated for Technical Group Vice Chair by the European Commission and the United States.
- United Kingdom has been nominated for Technical Group Vice Chair by China.

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

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

1. Purpose of the CSLF

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

2. Function of the CSLF

The CSLF seeks to:

2.1 Identify key obstacles to achieving improved technological capacity;

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

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

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

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

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

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

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.

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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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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CSLF Technology Roadmap Interim Report

Executive Summary and Conclusions

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 CSLF Technology Roadmap (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.

Overall, except for a very few niche industrial sector applications, for the current 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, mainly because of policy and economic barriers that currently exist. The technical readiness of these technologies were perceived, in general, as ready for large-scale commercial deployment.

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 not only technologies, but also regulatory policies and approaches toward project financing 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 any remaining 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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Introduction

The 2013 CSLF 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.
- 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.

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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 in the following ten sections.

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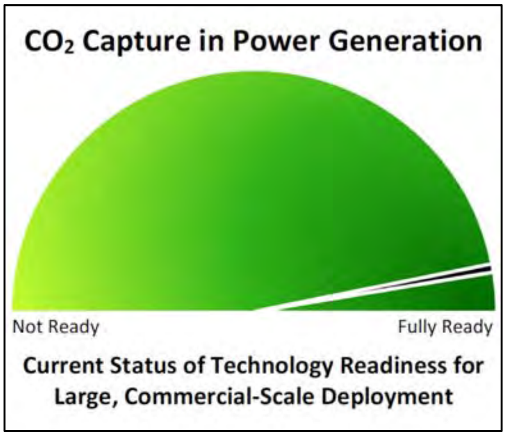
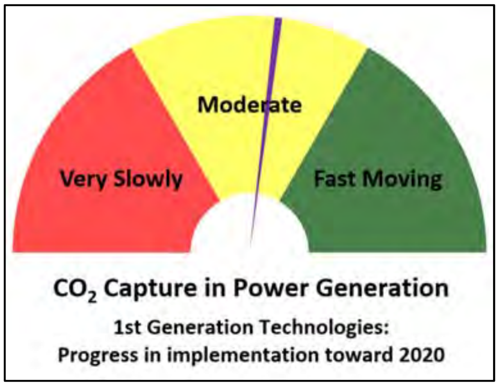
Global Trends in CO_2 Capture Technology from Power Industry

Technology Readiness

CCS experts from around the world consider CO_2 capture technology as fully ready for large scale demonstration, from a technology point of view. However, when taking barriers to implementation into account, the overall progress toward wide-scale use of CO_2 capture technology by the year 2020 has been only moderate.

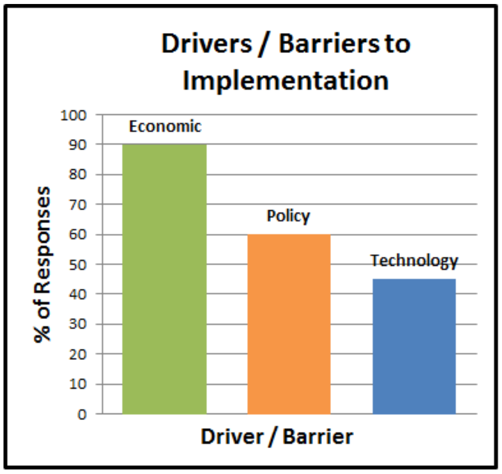
As of mid-2015, only one power station, Boundary Dam in Canada, is utilizing CO_2 capture technology in a large-scale project. Since 2013, more power production CCS projects have been cancelled than have been announced.





Barriers to Implementation

CCS experts have indicated that the most significant barriers to commercial-scale deployment of CO_2 capture technology are related to economics and policy. High cost, moderate public funding and limited regulations and incentives have been cited. The technical barriers are both minimal and manageable. Two potential technical challenges 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.



Next Generation Technologies

Development of next-generation technologies will reduce the cost of CO_2 capture. These next generation technologies are already being advanced at the R&D scale but they will need to be scaled up and field tested in pilot plants. However, the development of these new technologies is largely a function of economics and policy regarding adoption of CCS as a low emissions technology.

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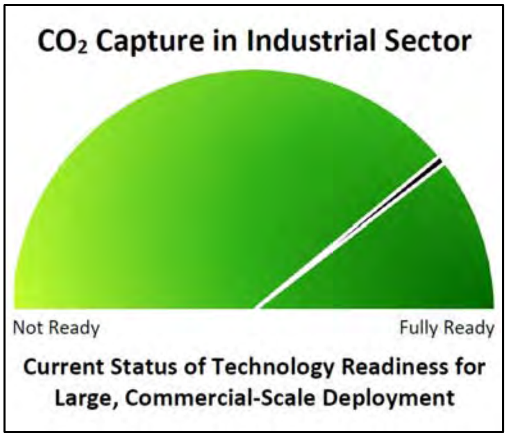
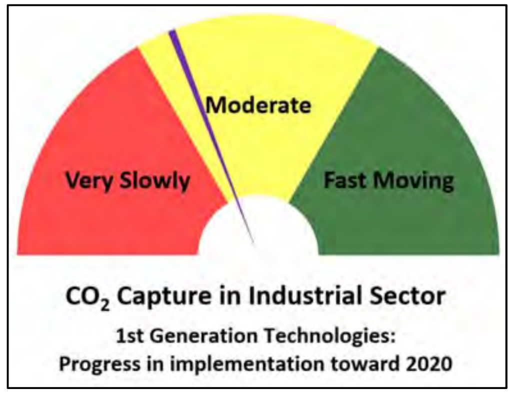
Global Trends in CO_2 Capture from Industrial Sector

Technology Readiness

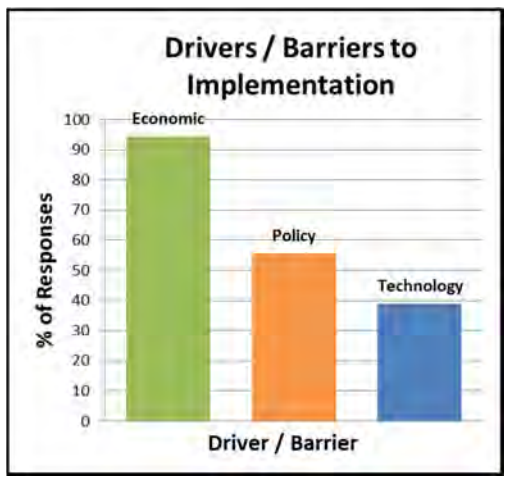
CCS experts from around the world rated the technical readiness of CO_2 capture technology differently depending on the industrial application. For liquified natural gas (LNG) processing, ethanol production and hydrogen production from reforming natural gas, CO_2 capture is an inherent part of the process and current technologies for doing so have progressed relatively rapidly. For the steel and cement industry, progress toward widescale use has been much slower. Overall, for most applications the technology is viewed as ready for large-scale demonstration but there is a need for more pilot projects.





Barriers to Implementation

CCS experts have indicated that the most significant barriers to commercial-scale deployment 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 also exist – operational challenges (e.g. contamination and intermittency) and integration issues – although the general view is that the technology for industrial applications is at a similar level of maturity as for application to power generation.



Next Generation Technologies

Development of next generation capture technologies has been very slow, although some applied R&D is taking place, in particular in the areas of bio-energy with CCS and in the cement industry. In some cases further R&D, focused on cost reduction and operational performance, is required before pilot-scale projects can happen. Development of these next generation technologies will be dependent on economics and policy regarding adoption of CCS as a low emissions technology.

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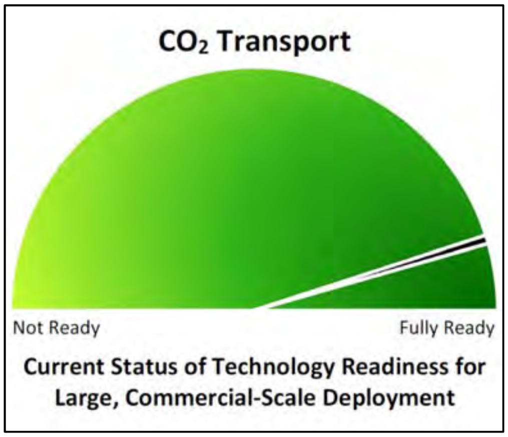
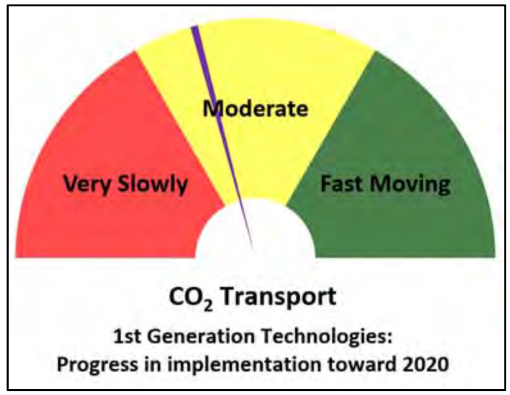
Global Trends in CO_2 Transport

Technology Readiness

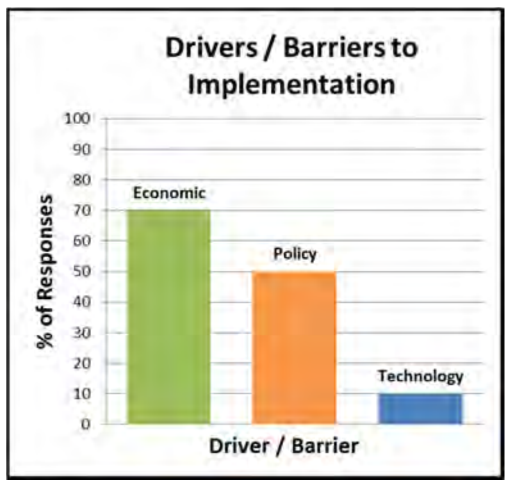
CCS experts consider the current generation of technologies for transporting CO_2 (by pipeline or by road/rail) are fully ready for large, commercial-scale deployment. However, non-technical barriers are inhibiting progress towards the 2020 goal of designing large-scale CO_2 transport networks and infrastructure. CO_2 for enhanced oil recovery (EOR) is being successfully transported in the United States, but the volumes are relatively small (approx. 60 million tonnes annually) and some of the pipelines are project-specific. Physical properties considerations for CO_2 (e.g., hydrate formation) and the purity of the captured CO_2 stream can complicate operational procedures and need to be considered, but there does not appear to be any insurmountable technical issues for onshore transport of CO_2.





Barriers to Implementation

CCS experts have confirmed that the most significant barriers to developing a CO_2 transportation infrastructure are related to economics and policy. CO_2 pipelines are very expensive to construct and there are currently insufficient policy drivers and incentives to bring about creation of a broadly-reaching CO_2 transport infrastructure. An additional challenge is that with the exception of current EOR operations, societal approval for routing of onshore CO_2 pipelines has proven to be extremely difficult to obtain – it was one of the factors that halted the Bełchatów CCS project in Poland.



Next Generation Technologies

Next generation hybrid CO_2 transport systems are under evaluation which involve both pipeline and ship transport. Several countries are investigating the feasibility of shipping CO_2 from onshore sources to offshore terminals where the CO_2 would be injected into sub-seabed geologic reservoirs. As with the current generation of transport systems, there does not appear to be any insurmountable technical issues for this kind of CO_2 transport.

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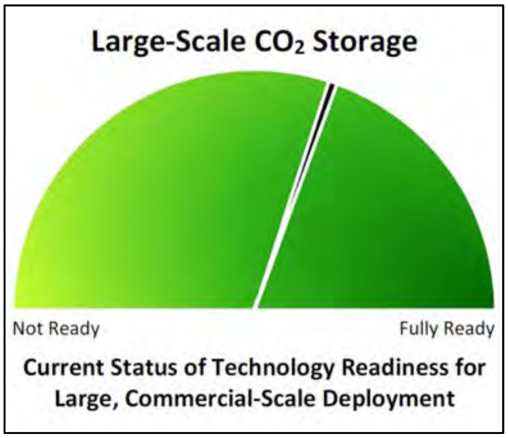
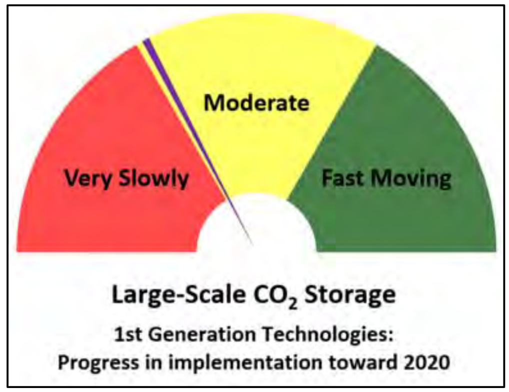
Global Trends in Large-Scale CO_2 Storage

Technology Readiness

CCS experts consider that technologies are reasonably developed to demonstrate large-scale CO_2 geologic storage. But when taking barriers to implementation into account, the overall progress toward large-scale storage has been slow. Whereas the International Energy Agency, for example, set a goal of 200 million tonnes (Mt) of CO_2 storage by 2020 in their CCS roadmap of 2013, the total capture capacity of the 14 operational large-scale CCS projects is limited to 28 Mt of CO_2.

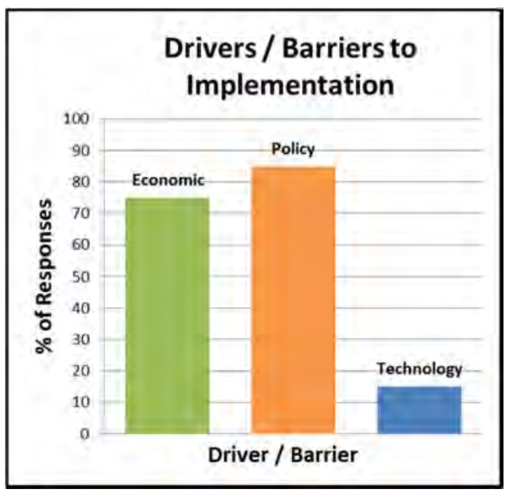
From a technology viewpoint, the remaining uncertainties involve the determination of storage capacities for individual geologic storage sites and the prediction of long-term CO_2 behavior in a reservoir. Both of these are site-specific and can be addressed by site characterization procedures, though these can take time and resources to accomplish. Each new storage project will add to the overall knowledge base such that uncertainties of this nature can be expected to lessen for each new storage project.





Barriers to Implementation

CCS experts have pointed to policy and economics barriers that are inhibiting implementation. These include uncertainties in long-term liability. And since CO_2 aquifer storage in general provides no revenue to compensate costs of CCS, policy-driven incentives are the only reason for undertaking a CCS project with non-EOR storage. Another critical barrier in some areas is public acceptance for onshore CO_2 storage.



Next Generation Technologies

Large-scale CO_2 storage sites are geologically sedimentary in nature. There have been studies of the efficacy of large-scale CO_2 storage under basalt, but there are not yet any projects of this nature at a large scale.

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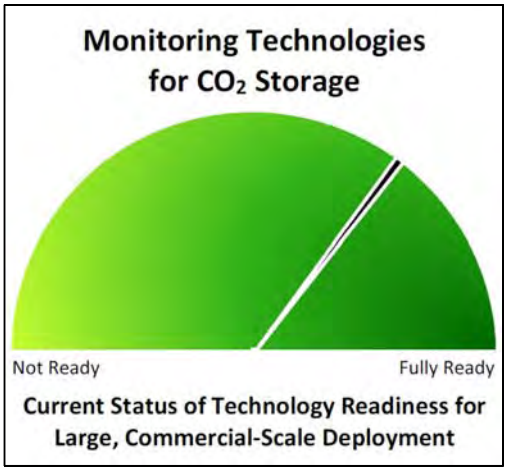
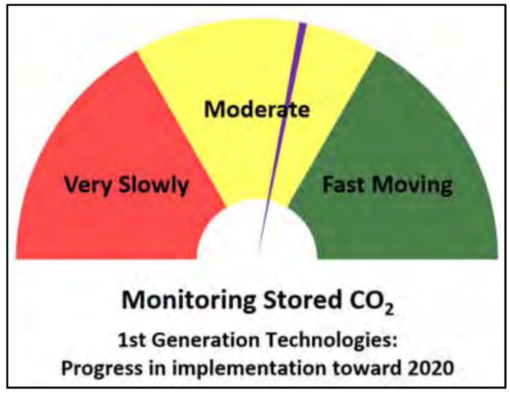
Global Trends in Monitoring Technologies for CO_2 Storage

Technology Readiness

CCS experts consider monitoring technologies for CO_2 storage as improving and progressing, and in general ready for large-scale demonstration. However, when taking barriers into account, the overall progress toward wide-scale use of these technologies is showing only moderate progress.

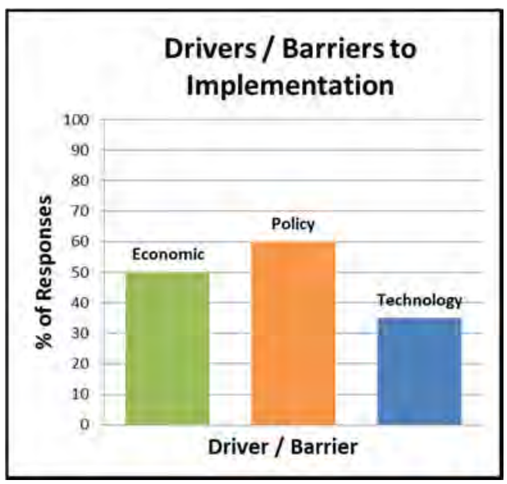
Technologies previously developed for the oil and gas industry are proving to be good techniques for monitoring storage of CO_2. The challenge has been gaining enough experience at large-scale field sites to prove reliability. EOR sites, Norway's offshore Sleipner project, and small-scale field tests have provided opportunities to broaden the knowledge base and contribute to scientific understanding.





Barriers to Implementation

CCS experts have indicated there are significant economic and policy barriers to commercial-scale deployment of CO_2 monitoring technologies. The lack of large-scale test sites and the fact that most technology development and field tests are government-funded are commonly cited issues. Monitoring technology itself was not necessarily considered a barrier as projects will use what technologies and tools are available. However, some of these technologies, such as seismic, are considered too costly or of low precision.



Next Generation Technologies

Current monitoring technologies are limited or have too much uncertainty regarding the exact CO_2 plume size and understanding complex geology and fluid flow. The contribution of government funding to progressing next generation technologies is recognized as a key contributor to advancing monitoring technologies, but large-scale sites are needed for technology validation.

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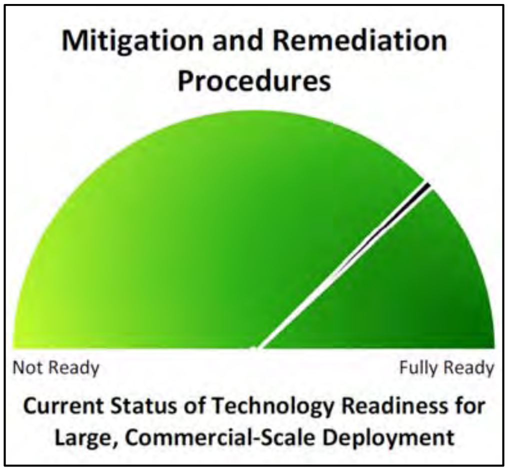
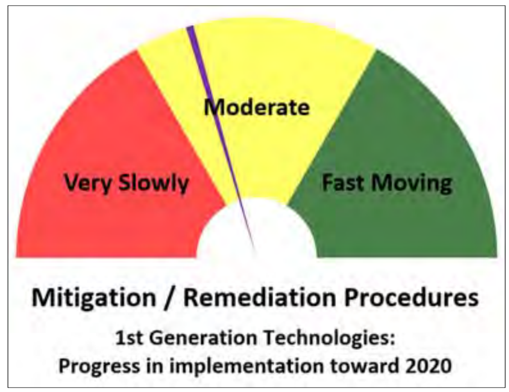
Global Trends in Mitigation and Remediation Procedures

Technology Readiness

CCS experts regard the mitigation and remediation procedures as being ready for large-scale demonstration, from a technology point of view, largely because they rely on methods that have been well-tested and deployed in oil and gas as well as ground water industries. The current solutions are, however, costly and challenging to deploy. The technology still needs demonstration for a variety of settings (geology, operational parameters, leak event type, etc.), and it needs research and development of (more) cost efficient methods.

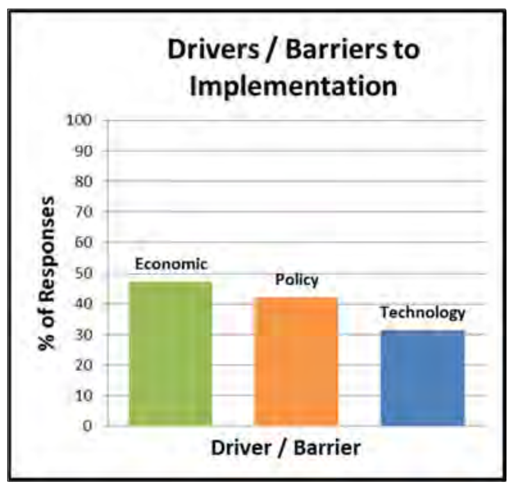
Overall, the commercial and environmental potential of these technologies and procedures has been recognized, and it is acknowledged that they should be in place before CCS can be deployed. But when taking barriers to implementation into account, actual progress toward their use has been slow to moderate.





Barriers to Implementation

CCS experts have indicated that there are still some economics and policy barriers that are inhibiting wide-scale use of these technologies and procedures. For example, there is no obvious consensus as to what constitutes a leakage and hence when a regulator might require remediation.



Technical barriers are also present. Mitigation and remediation, as "end of chain" technologies, have received much less attention than CO_2 capture, transport and storage. Some of these technologies and procedures are in a relatively early stage, and their development should be accelerated. 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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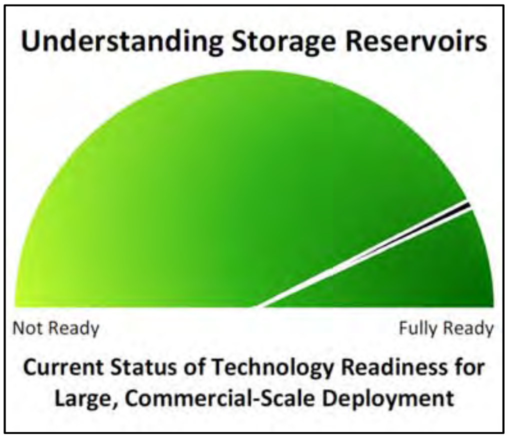
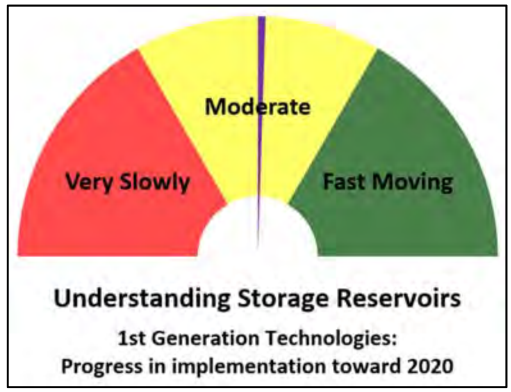
Global Trends in Understanding Storage Reservoirs

Technology Readiness

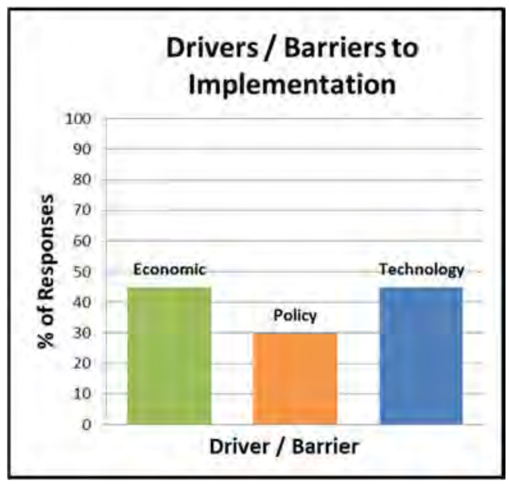
CCS experts regard the technologies involved in the understanding of storage reservoirs to be ready for wide-scale use but that barriers to implementation are reducing progress toward wide-scale use to only a moderate rate. Commercial CO_2 storage operations at existing large-scale CCS projects are providing an expanding source of experience and are of great value to future projects. These projects have generally adopted oil & gas industry best practices for CO_2-EOR and storage in deep saline formations, and their use has led to advancements.





Barriers to Implementation

CCS experts cite economic, technology, and policy barriers to commercial-scale use. Deploying conventional geological, geochemical and geophysical techniques at commercial scale is expensive, even though such approaches have provided detailed characterization of potential storage reservoirs. Other cost barriers exist, generally linked to the high cost of using oil & gas industry techniques in CCS applications. There are also still some technology-related barriers. The prediction of CO_2 plume behavior using modelling techniques is not straightforward and pressure management in reservoirs is a critical factor.



Next Generation Technologies

Understanding storage reservoirs for large-scale, commercial CCS operations has proved more difficult than first predicted. RD&D into advanced technologies and techniques that can further reduce residual subsurface uncertainties following site characterization using costly conventional approaches is needed. Cost-effectively reducing this uncertainty during site characterization will significantly reduce characterization time, development cost, operational risks and closure liability. Characterization and site selection link with regulatory requirements for site monitoring, and cost reduction in site monitoring is a key requirement.

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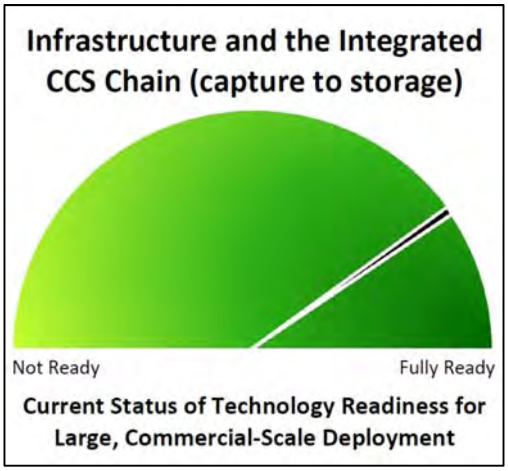
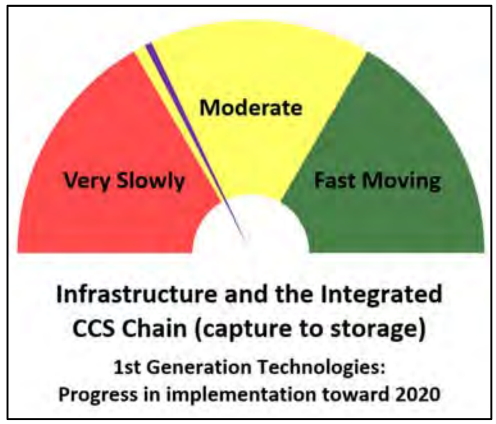
Global Trends in Infrastructure and the Integrated CCS Chain (Capture to Storage)

Technology Readiness

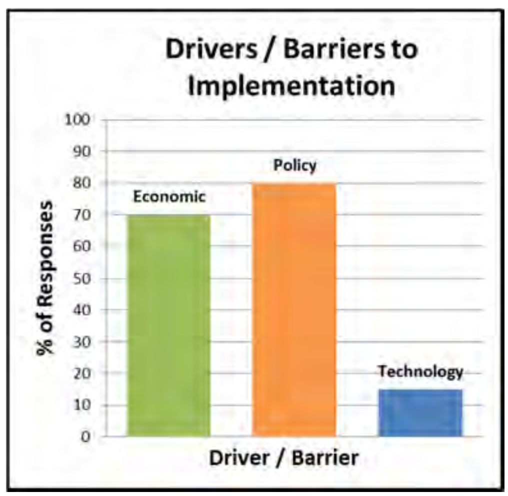
CCS experts consider infrastructure-related technologies involving the integrated CCS chain to be ready for large-scale demonstration. There are significant economic and policy-related barriers, however, that are inhibiting 'CCS hub' projects from happening. Projects such as the ROAD project in the Netherlands have 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.





Barriers to Implementation

CCS experts have indicated that the most commonly cited barriers to commercial-scale deployment are the general lack of policy and difficult economics, including finance, ownership, business cases, risk allocation, etc. While technical issues are not generally considered to be barriers, CO_2 purity (especially where multiple sources are involved) could be a major issue. Also, plant and grid flexibility will need careful management.



Next Generation Technologies

New technologies related to infrastructure and the integrated CCS chain may not actually be necessary, but there is a need to find better ways of adapting many of the existing technologies to industrial processes with CCS (e.g., chemicals plants, iron and steel, cement, etc.). Furthermore, multiple sources linked via 'hubs' to geologic storage sites will pose challenges that are not currently being addressed through R&D activities.

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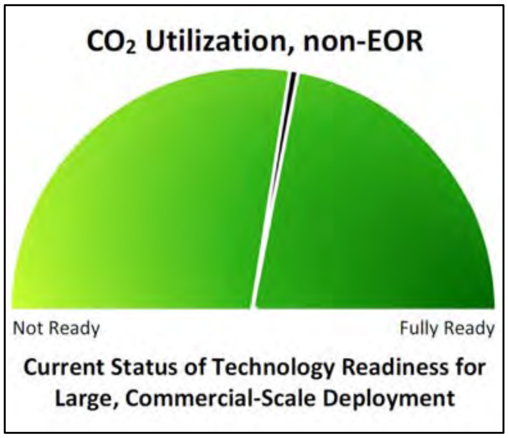
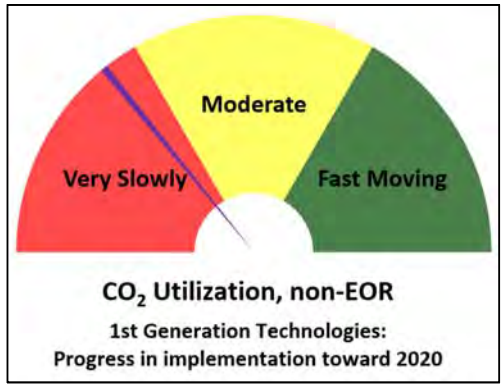
Global Trends in CO_2 Utilization, non-EOR

Technology Readiness

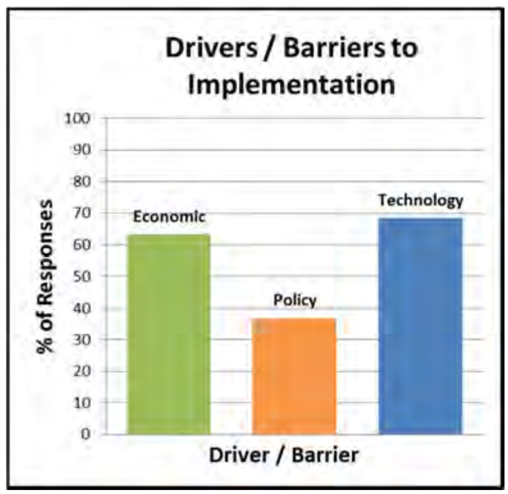
CCS experts consider the current generation of technologies for non-EOR CO_2 utilization at least somewhat ready for large-scale demonstration, though this determination is application specific. There may be some technologies which are ready for some niche applications but for most options, good business cases are lacking due to the high-cost and energy-intensive features for non-EOR CO_2 utilization. Overall progress toward wide-scale use of these technologies is in general very slow moving.





Barriers to Implementation

CCS experts have indicated that the most significant barriers to implementation of these technologies are related to economics and technology. In particular, the current generation of technologies can make use of only a relatively small volume of CO_2 compared to EOR, so a relatively small amount of attention is being paid to these technologies in the overall scheme of things. As a result, development of technologies for utilization of CO_2 have not been advancing as rapidly as for other aspects of CCS and the economic case for these new technologies is still a work in progress.



Next Generation Technologies

Development of next generation technologies for non-EOR CO_2 utilization is also moving very slowly, but there has been special attention from governments (especially in China) for promoting the development of new and advanced utilization technologies.

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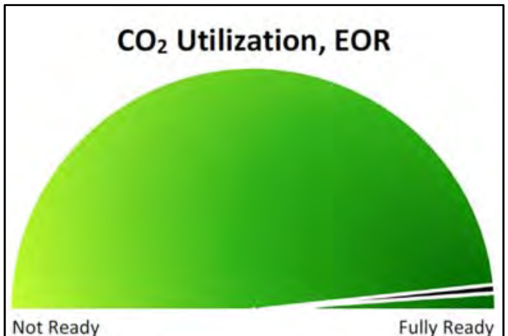
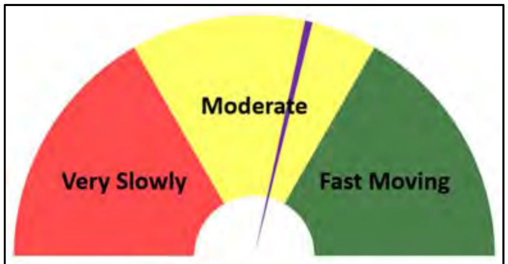
Global Trends in CO_2 Utilization, Enhanced Oil Recovery (EOR)

Technology Readiness

CCS experts consider CO_2-EOR as a deployed technology that is fully ready for large-scale demonstration but its widespread implementation around the world has been limited because of applicability, economics, or policy barriers. In the United States, CO_2-EOR has been in commercial use for more than 40 years. 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.



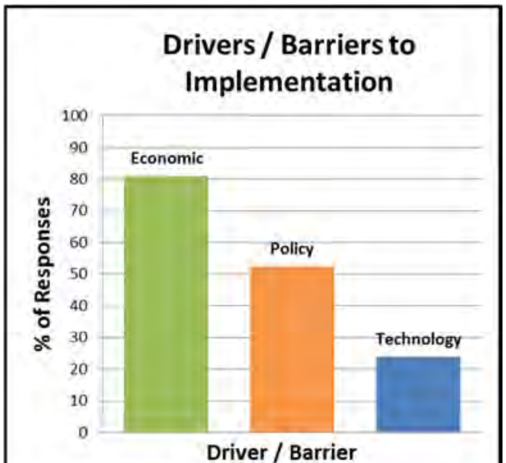
Current Status of Technology Readiness for Large, Commercial-Scale Deployment



CO_2 Utilization, EOR
1st Generation Technologies:
Progress in implementation toward 2020

Barriers to Implementation

CCS experts have indicated that the most significant barrier to wide-scale deployment of CO_2-EOR 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 considered economical (at current oil prices). Another economic barrier is the high cost of constructing additional infrastructure to move the CO_2 from large point sources to EOR locations; there are few places in the world where such infrastructure currently exists. Policy-related barriers also exist, where goverment support and incentives have been in general insufficient to enable wider-scale deployment.



Next Generation Technologies

Development of next generation CO_2-EOR has been slow moving, like its application in unconventional reservoirs and enhanced coal-bed methane (ECBM), and in extending its purpose to include CO_2 storage. Using CO_2-EOR for CO_2 storage requires new monitoring techniques to cover areas beyond the conventional monitored areas in EOR, to include a wider range of parameters, and to be extended for longer periods of time beyond the operational time of the oil field.

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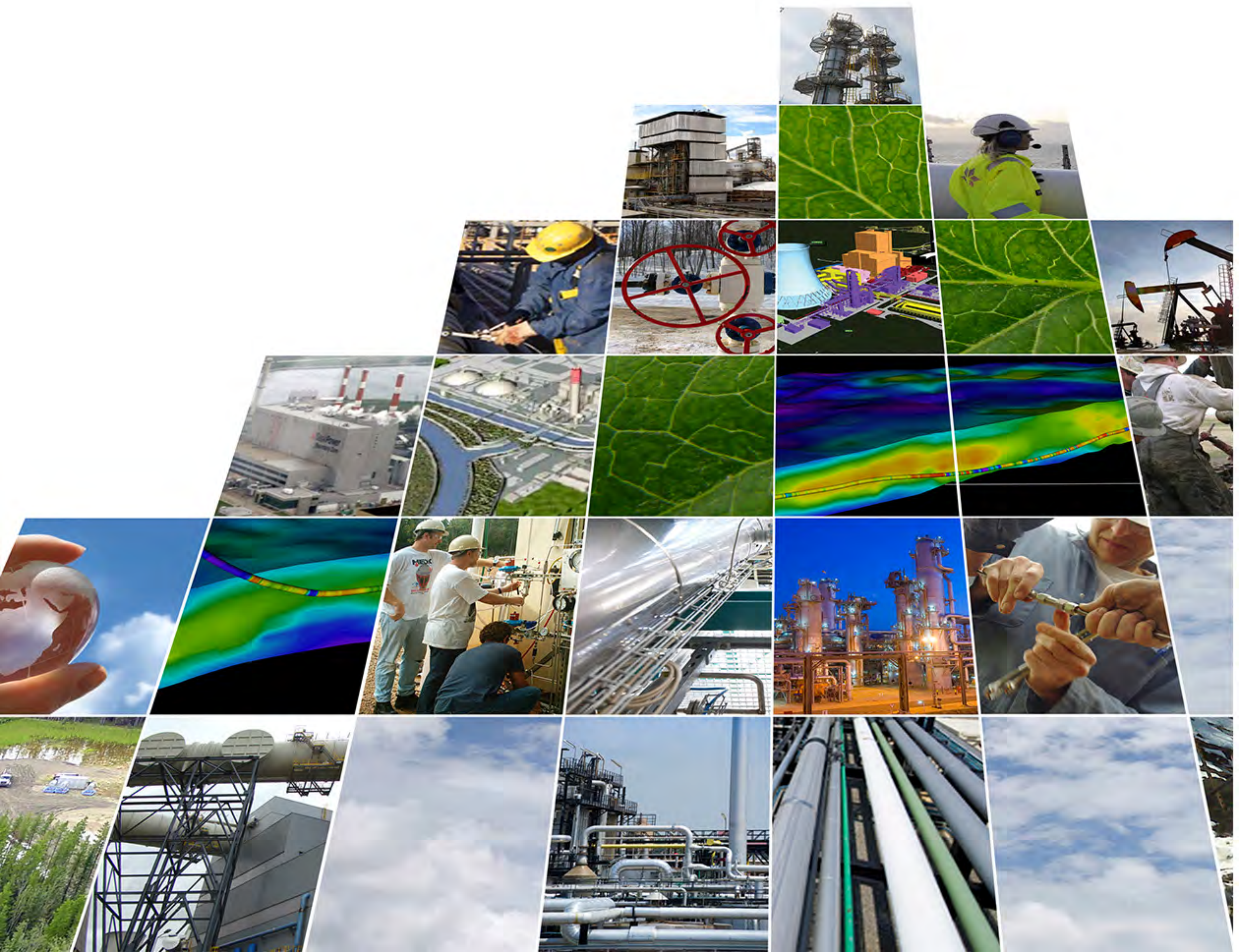
carbon
sequestration leadership forum

2013

Carbon Sequestration

TECHNOLOGY ROADMAP



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Executive Summary

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

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

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

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

Key conclusions of the TRM are:

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

conditions, and data collection for site characterization, qualification[1] and permitting currently requires a long lead-time (3-10 years). Identified research, development and demonstration (RD&D) actions need to:
  - intensify demonstration of sizeable storage in a wide range of national and geological settings, onshore as well as offshore;
  - further test to validate monitoring technologies in large-scale storage projects and qualify and commercialize these technologies for commercial use;
  - develop and validate mitigation and remediation methods for potential leaks and up-scale these to commercial scale;
  - further develop the understanding of fundamental processes to advance the simulation tools regarding the effects and fate of the stored CO_2; and
  - agree upon and develop consistent methods for evaluating CO_2 storage capacity at various scales and produce geographic maps of national and global distribution of this capacity.
- There are no technical challenges per se in converting CO_2-EOR operations to CCS, although issues like availability of high quality CO_2 at an economic cost, infrastructure for transporting CO_2 to oil fields; and legal, regulatory and long-term liability must be addressed for this to happen.
- There is a broad array of non-EOR CO_2 utilization options that, when taken cumulatively, can provide a mechanism to utilize CO_2 in an economic manner. However, these options are at various levels of technological and market maturity and require:
  - technology development and small-scale tests for less mature technologies;
  - technical, economic, and environmental analyses to better quantify impacts and benefits; and
  - independent tests to verify the performance of any products produced through these other utilization options.
- Public concern and opposition to pipelines for CO_2 transport and geological storage of CO_2 in some countries is a major concern. Further RD&D on storage that includes the elements above and improves aspects of risk management of CO_2 transport and storage sites will contribute to safe long-term storage and public acceptance. The results should be communicated in plain language.

Priority Actions Recommended for Implementation by Policy Makers

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

Towards 2020 nations should work together to:
- Maintain and increase commitment to CCS as a viable greenhouse gas (GHG) mitigation option
- Establish international networks, test centres and comprehensive RD&D programmes to verify, qualify and facilitate demonstration of CCS technologies

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

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

Towards 2030 nations should work together to:

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

Towards 2050 nations should work together to:

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

Recommendations for Follow-Up Plans

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

1. Objectives, Scope and Approach of TRM

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

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

The TRM sets out to give answers to three questions:

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

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

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

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

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

This document was prepared using the following approach:

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

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

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

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

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

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

2. Vision and Target - the Importance of CCS

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

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

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

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

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

3. Assessment of Present Situation

3.1. Implementation

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

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

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

3.2. Capture

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.3. Transport

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

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

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

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

3.4. Storage

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.5. Infrastructure and the Integrated CCS Chain

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

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

3.6. Utilization

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

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

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

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

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

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

4. Identified Technology Needs

4.1. Capture

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

Hence, in pursuing 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.

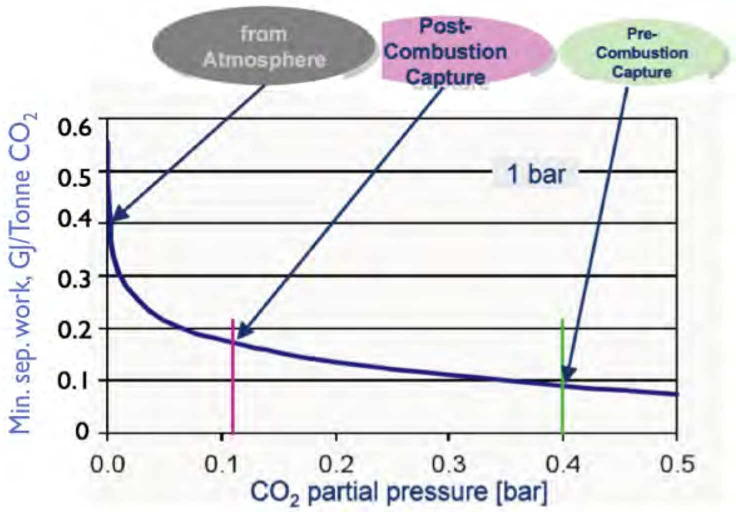

Figure 1: Theoretical minimum separation work of CO_2 from a flue gas depending on the partial pressure of CO_2 [modified from Bolland et al., 2006]

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.

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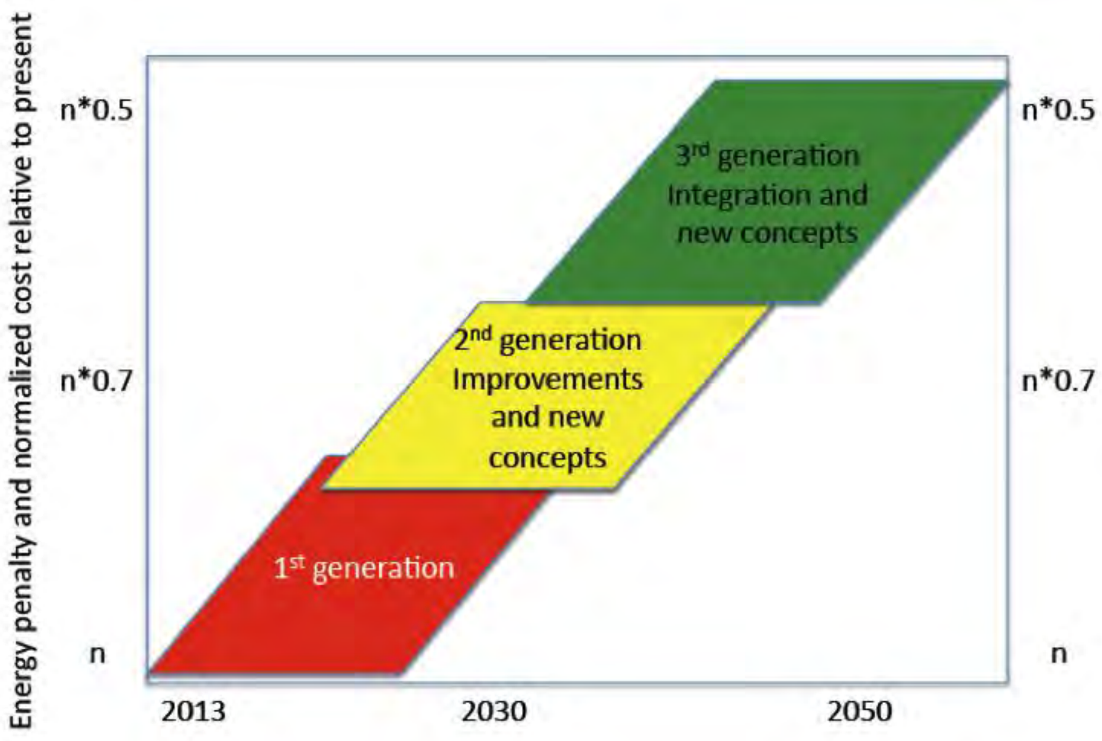

Figure 2: Priorities for CCS technology development. The energy penalty and normalized costs are shown in relation to the present level (n), i.e. equivalent to reduction by 30% in 2030 and 50% towards 2050.

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.

4.3. Storage

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

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

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

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

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

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

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

Other issues that need RD&D are:

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

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

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

4.3.1. Recommendation 4: Large-Scale CO_2 Storage

Towards 2020:

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

Towards 2030:

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

Towards 2050:

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

4.3.2. Recommendation 5: Monitoring and Mitigation/Remediation

Towards 2020:

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

Towards 2030:

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

4.3.3 Recommendation 6: Understanding the Storage Reservoirs

Towards 2020:

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

4.4. Infrastructure and the Integrated CCS Chain

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

Other RD&D needs include:

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

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

4.4.1. Recommendation 7: Infrastructure

Towards 2020:

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

Towards 2030:

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

4.5. Utilization

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

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

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

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

4.5.1. Recommendation 8: CO_2 Utilization

Towards 2020:

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

5. Priority Actions Recommended for Implementation by Policy Makers

Towards 2020 nations should work together to:

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

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

Towards 2030 nations should work together to:

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

Towards 2050 nations should work together to:

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

6. Summary and Follow-Up Plans

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

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

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

Through the CSLF Secretariat, the PIRT will:

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

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

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Abbreviations and Acronyms

2DS	IEA ETP 2012 2°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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Carbon Sequestration Leadership Forum
www.cslforum.org

Active and Completed CSLF Recognized Projects

(as of October 2015)

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, demonstrated, from economic and environmental criteria, the overall feasibility of coal bed methane 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 where the CO_2 can be stored in saline aquifers in the 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** ***(Completed)***
Nominators: Netherlands (lead) and Germany
This was 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 was 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 provided an information pathway toward large-scale implementation of CO_2 geological storage throughout Europe. This was a three-year project, started in November 2011, and 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 was 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** ***(Completed)***
Nominators: United Kingdom (lead) and United States
This was a collaborative venture of seven partner companies (international oil and gas producers) plus the Electric Power Research Institute. The overall goals of the project were 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 was comprised of four areas: CO_2 Capture; Storage Monitoring & Verification; Policy & Incentives; and Communications. A fifth activity, in support of these four teams, was Economic Modeling. This third phase of the project included 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 continued into 2014.
Recognized by the CSLF at its Beijing meeting, September 2011

12. **CO2CRC Otway Project Stage 1** ***(Completed)***
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

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(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 United Kingdom. The project was successful in developing sound scientific methodologies for the assessment, planning, and long-term monitoring of underground

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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 input for developing 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 was intended to lay the groundwork for a future advanced commercial-scale power plant with hydrogen production and CO_2 management. 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

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

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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 was a monitoring activity for a large-scale project that utilizes CO_2 for enhanced oil recovery (EOR) at a Canadian oil field. The goal of the project was 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 encompassed 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, integrated with policy research, were incorporated into 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. Jingbian CCS Project

Nominators: China (lead) and Australia

This integrated large-scale pilot project, located at a coal-to-chemicals company in the Ordos Basin of China's Shaanxi Province, is capturing CO_2 from a coal gasification plant via a commercial chilled methanol process, transporting the CO_2 by tanker truck to a nearby oil field, and utilizing the CO_2 for EOR. The overall objective is to demonstrate the viability of a commercial EOR project in China. The project includes capture and injection of up to about 50,000 tonnes per year of CO_2. There will also be a comprehensive MMV regime for both surface and subsurface monitoring of the injected CO_2. This project is intended to be a model for efficient exploitation of Shaanxi Province's coal and oil resources, as it is estimated that more than 60% of stationary source CO_2 emissions in the province could be utilized for EOR.

Recognized by the CSLF at its Regina meeting, June 2015

30. 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

31. 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

32. 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

33. 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

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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

34. 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

35. 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

36. Regional Carbon Sequestration Partnerships
Nominators: United States (lead) and Canada
This multifaceted project will identify and test the most promising opportunities to implement sequestration technologies in the United States and Canada. There are seven different regional partnerships, each with their own specific program plans, which will conduct field validation tests of specific sequestration technologies and infrastructure concepts; refine and implement (via field tests) appropriate measurement, monitoring and verification (MMV) protocols for sequestration projects; characterize the regions to determine the technical and economic storage capacities; implement and continue to research the regulatory compliance requirements for each type of sequestration technology; and identify commercially available sequestration technologies ready for large-scale deployment.
Recognized by the CSLF at its Berlin meeting, September 2005

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37. Regional Opportunities for CO_2 Capture and Storage in China *(Completed)*

Nominators: United States (lead) and China

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

Recognized by the CSLF at its Berlin meeting, September 2005

38. 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

39. SaskPower Integrated CCS Demonstration Project at Boundary Dam Unit 3

Nominators: Canada (lead) and the United States

This large-scale project, located in the southeastern corner of Saskatchewan Province in Canada, is the first application of full stream CO_2 recovery from flue gas of a commercial 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

40. 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

41. 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

42. 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

43. 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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44. 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.