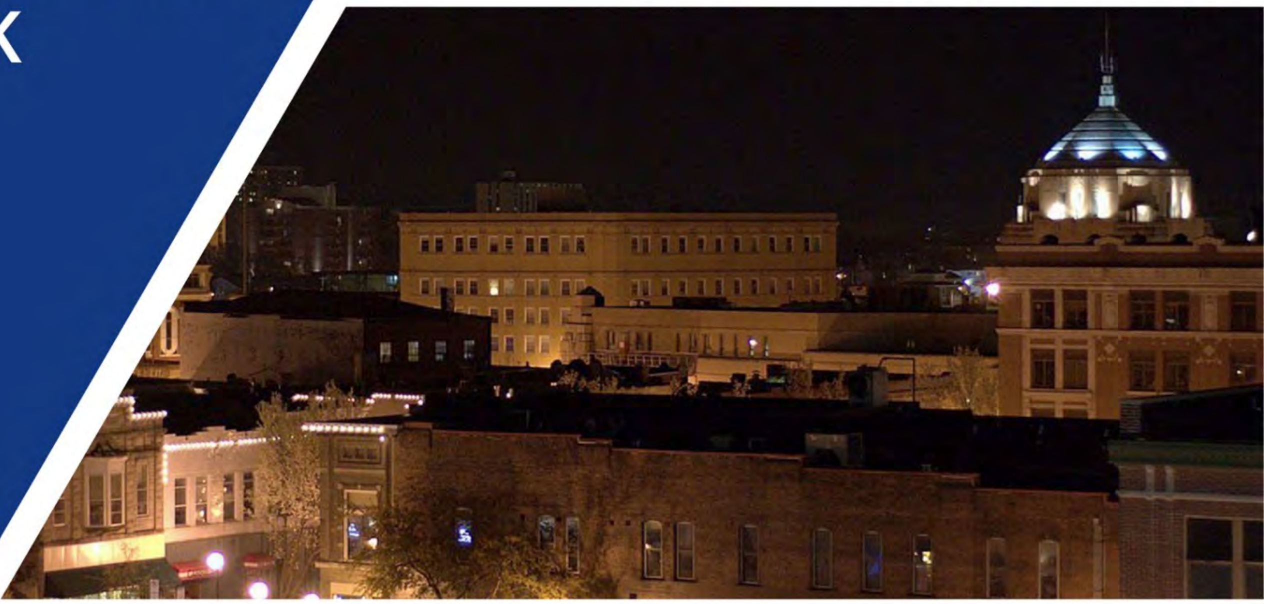
carbon sequestration leadership forum

MEETING DOCUMENTS BOOK

CSLF

2019 Mid-Year Technical Group Meeting



Champaign, Illinois
United States
April 25–26, 2019

Carbon Sequestration Leadership Forum

www.cslforum.org

2019 CSLF TECHNICAL GROUP MID-YEAR MEETING DOCUMENTS BOOK

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Carbon Sequestration Leadership Forum

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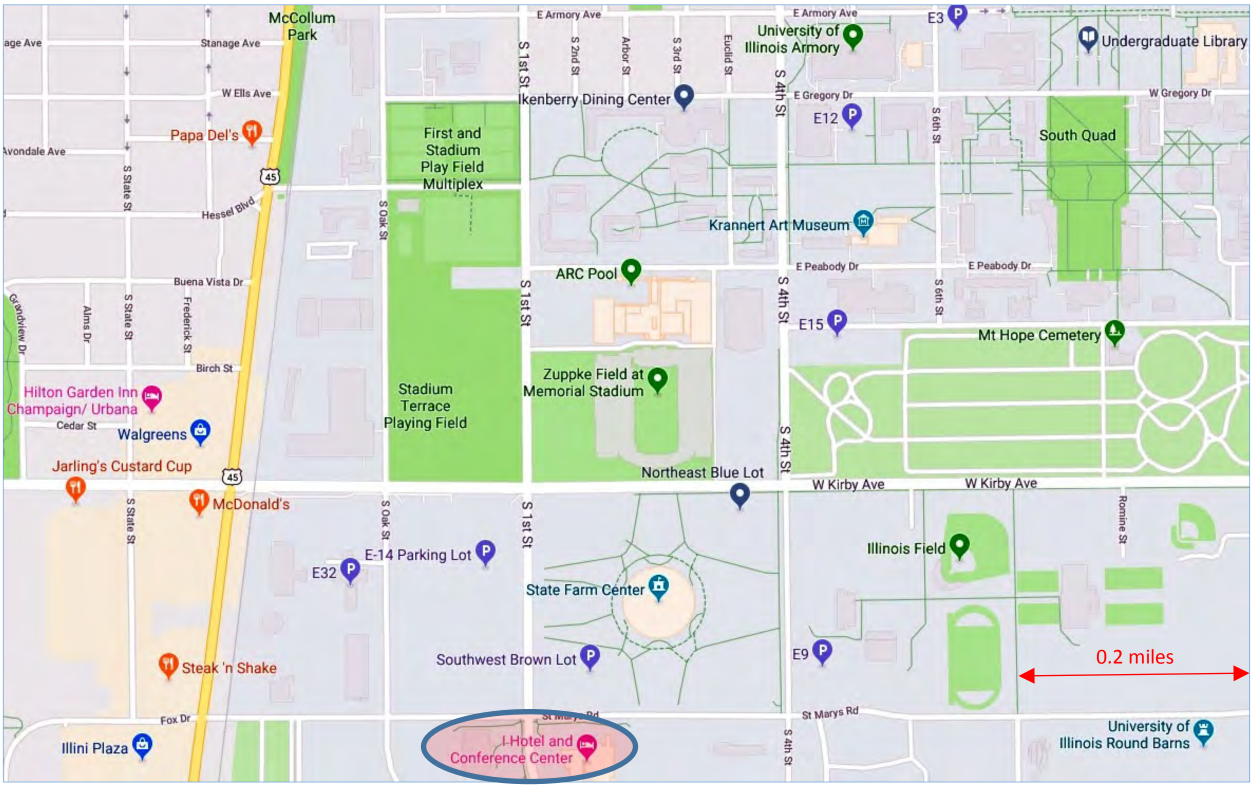
OVERALL SCHEDULE

2019 Mid-Year CSLF Technical Group Meeting
Champaign, Illinois, USA

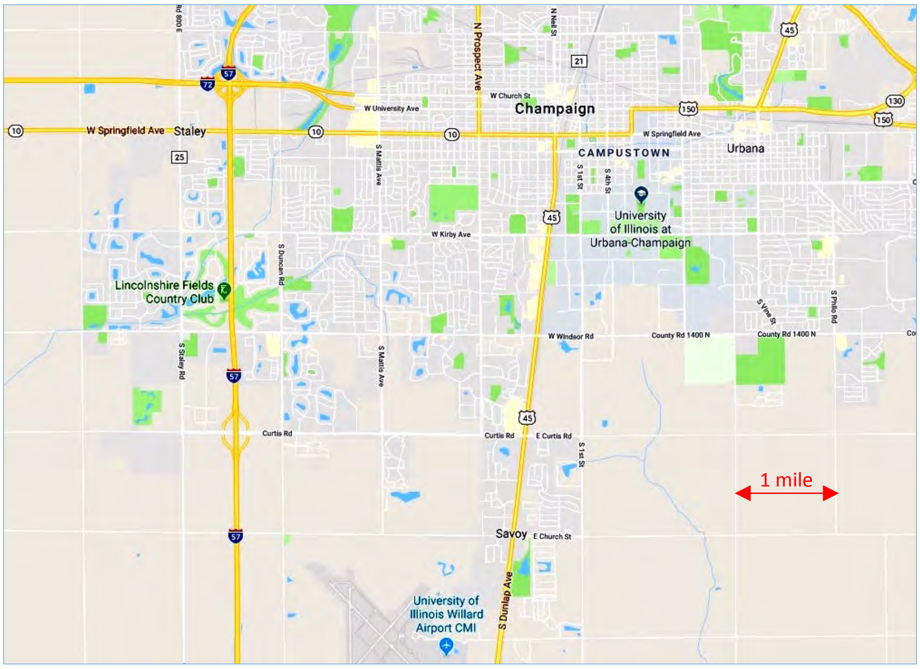
	Tuesday April 23	Wednesday April 24	Thursday April 25	Friday April 26
Morning	**Short Course** (not part of CSLF meeting) *ISGS Core Facility* *(starts at 11:00am)*	**MGSC Annual Meeting** (not part of CSLF meeting) *Chancellor Ballroom,* *I Hotel* *(starts at TBD)*	**Field Trip** *(Bus departs at 8:30am; returns by 2:00pm)*	**Meeting of CSLF Technical Group** (continues) *Alma Mater Room,* *I Hotel* *(starts at 8:30am)*
Afternoon	**Short Course** (continues) *(ends at 3:00pm)*	**MGSC Annual Meeting** (continues)	**Meeting of CSLF Technical Group** *Alma Mater Room,* *I Hotel* *(3:00-6:30pm)*	**Meeting of CSLF Technical Group** (continues) *(ends at 3:00pm)*
Evening	**Early Registration** *(starts at 4:30pm)* **Welcome Event** (not part of CSLF meeting) *Lincoln Room,* *I Hotel* *(5:30-7:30pm)*	**Evening Event at Memorial Stadium** (not part of CSLF meeting) *(starts at 6:30pm)*		

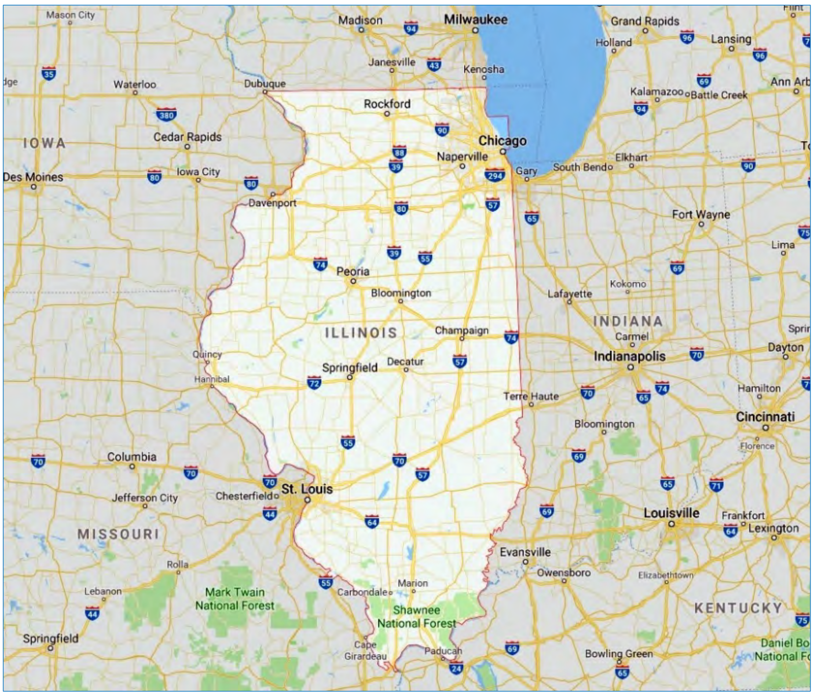
Meeting Venue Information

The 2019 CSLF Technical Group Mid-Year Meeting will take place on Thursday and Friday, April 25-26 in Champaign, Illinois, USA at the **I Hotel and Convention Center**, located on South 1st Street, not far from the University of Illinois campus. *(Note: The Mid-Year Meeting is being held in conjunction with the Midwest Geological Sequestration Consortium's Annual Meeting which begins on April 23. Please refer to the overall schedule for more details.)*



Rooms are available at the I Hotel for $139 per night when you book using the code MGSC2019. ***Please note that the I Hotel does not have rooms available for Friday, April 26.*** For that night it is recommended that you change to a hotel closer to your departure airport.





For those arriving the United States by air, the closest large international airports are located in Chicago (ORD) [approx. 150 miles/240 km by car], Indianapolis (IND) [approx. 125 miles/200 km], and St. Louis (STL) [approx. 185 miles/300 km]. There are also regional airports (with connecting flights to ORD) at Champaign (CMI) (American Airlines) and Bloomington (BMI) (Delta Airlines).

Site Visit to IBDP and IL ICCS Projects in Decatur

There will be a field trip to two CSLF-recognized projects: the Illinois Basin – Decatur Project (IBDP) and the Illinois Industrial CCS Project (IL ICCS) in Decatur, Illinois on the morning of Thursday, April 25.

Bus transportation will be provided for this trip. **Bus departs from I Hotel and Convention Centre at 8:30am.** Bus returns by approx. 2:00pm. The Technical Group meeting will begin at 3:00pm.

TO PARTICIPATE IN THE SITE VISIT, YOU MUST INDICATE YOUR INTEREST WHEN YOU REGISTER FOR THE MEETING USING THE ONLINE MEETING REGISTRATION FORM.

Agenda

Decatur Field Site Visit

Thursday, April 25, 2019

8:00 a.m.	Busses depart from front door of I Hotel (near hotel lobby) to travel to IBDP trailer at ADM Facility in Decatur, Illinois
9:00 – 9:05 a.m.	Welcome and introductions, safety briefing
9:05 – 9:45 a.m.	Decatur CCS Projects Overview, Sallie Greenberg, ISGS
9:45 – 9:55 a.m.	Distribute PPE, divide into working groups for tour (bus groups)

Two Stations:

- STATION A – Well construction and completions, demonstration of data collection systems, view CCS1 and GM1 wells with group photo (Nick Malkewicz, Projeo Corporation)
- STATION B – MVA activities, view VW1 or VW2 [depending on weather] (Bracken Wimmer and Abbas Iranmanesh, ISGS)

Schedule for Rotation:

	9:55 – 10:25 a.m.	10:35 – 11:05 a.m.
Bus 1 (Sallie Greenberg)	A – Well Operations	B – MVA Activities
Bus 2 (Randy Locke)	B – MVA Activities	A – Well Operations

11:15 a.m.	Travel to and tour National Sequestration Education Center (NSEC), Richland Community College Campus
11:45 a.m.	Drive-by tour of the ICCS project site and travel back to I Hotel, Champaign, Illinois

Draft: 18 April 2019
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Technical Group Meeting

I Hotel and Convention Center
Alma Mater Room
Champaign, Illinois, USA
25-26 April 2019

Thursday, 25 April 2019

2:00-3:00pm **Meeting Registration**

3:00-4:30pm **Technical Group Meeting**

1. **Welcome and Opening Statement** *(5 minutes)*
   Åse Slagtern, Technical Group Chair, Norway

2. **Host Welcome** *(5 minutes)*
   Mark Ryan, Executive Director of Prairie Research Institute, University of Illinois, United States

3. **Introduction of Delegates** *(10 minutes)*
   Delegates

4. **Adoption of Agenda** *(2 minutes)*
   Åse Slagtern, Technical Group Chair, Norway

5. **Approval of Minutes from Melbourne Meeting** *(2 minutes)*
   Åse Slagtern, Technical Group Chair, Norway

6. **Report from Secretariat** *(6 minutes)*
   Richard Lynch, CSLF Secretariat

7. **Update from the CO_2GeoNet Association** *(15 minutes)*
   Ceri Vincent, President, CO_2GeoNet Association

8. **Update from the IEA Greenhouse Gas R&D Programme** *(15 minutes)*
   Tim Dixon, Programme Manager, IEAGHG

9. **Update from the Global CCS Institute** *(15 minutes)*
   Rob Mitchell, Senior Client Engagement Lead, GCCSI

10. **Update on Mission Innovation** *(15 minutes)*
    Brian Allison, United Kingdom

4:30-4:45pm **Refreshment Break**
Foyer outside Meeting Room

4:45-6:30pm **Continuation of Meeting**

11. **PIRT Report** *(20 minutes)*
    - Approval of Summary from PIRT Meeting of October 2018
    - PIRT Project Interaction Activities, Past and Future
    - Should PIRT functions and membership be revised?

    Martine Woolf, PIRT Chair, Australia
    Sallie Greenberg, United States
    Delegates

12. **Update from the CSLF Policy Group** *(15 minutes)*
Jarad Daniels, United States (presented by Mark Ackiewicz)

13. **Report from CCS for Energy Intensive Industries Task Force** *(15 minutes)*
Dominique Copin, Task Force Co-Chair, France

14. **Recommendations from Improved Pore Space Utilisation Task Force** *(5 minutes)*
Max Watson, Task Force Co-Chair, Australia
Brian Allison, Task Force Co-Chair, United Kingdom

15. **Report from Non-EHR Utilization Options Task Force** *(15 minutes)*
Mark Ackiewicz, Task Force Chair, United States

16. **Report from Hubs and Infrastructure Task Force** *(12 minutes)*
Lars Ingolf Eide, Norway

17. **Update on Technical Group Task Force Action Plan** *(10 minutes)*
Åse Slagtern, Technical Group Chair, Norway

18. **Engagement of Academic Community** *(12 minutes)*
Åse Slagtern, Technical Group Chair, Norway
Delegates

19. **Adjourn for the Evening** *(1 minute)*
Åse Slagtern, Technical Group Chair, Norway

Friday, 26 April 2019

8:30-10:20am **Continuation of Meeting**

20. **Welcome Back** *(5 minutes)*
Åse Slagtern, Technical Group Chair, Norway

21. **Overview of Department of Energy-sponsored CCUS Activities** *(30 minutes)*
Mark Ackiewicz, Department of Energy, United States

22. **Update from CSLF-recognized Project:**
NET Power 50 MW_{th} Allam Cycle Demonstration Project *(25 minutes)*
Adam Goff, NET Power, United States

23. **Update from CSLF-recognized Project:**
Michigan Basin Development Phase Project *(25 minutes)*
Neeraj Gupta, Battelle, United States

24. **Update from CSLF-recognized Project:**
SECARB Early Test at Cranfield Project *(25 minutes)*
Susan Hovorka, University of Texas Bureau of Economic Geology, United States

10:20-10:35am **Refreshment Break**
Foyer outside Meeting Room

10:35-12:15pm **Continuation of Meeting**

25. **Update from CSLF-recognized Projects:**
CCSI and NRAP *(25 minutes)*
Grant Bromhal, National Energy Technology Laboratory, United States

26. **Update from Petra Nova Project** *(25 minutes)*
Greg Kennedy, NRG Energy, United States

27. **New Materials Discovery in Solvents and Membranes** *(25 minutes)*
Jan Steckel, NETL, United States

28. **Project Tundra: Developing the World's Largest Integrated Post-Combustion Carbon Capture Unit** *(25 minutes)*
John Harju, University of North Dakota Energy & Environmental Research Center, United States

12:15-1:30pm **Lunch**
Location TBA

1:30-3:00pm **Continuation of Meeting**

29. Update on International Test Center Network *(15 minutes)*
Frank Morton, National Carbon Capture Center, United States

30. Report from Ad Hoc Committee for Task Force Maximization and Knowledge Sharing Assessment *(50 minutes)*
Sallie Greenberg, Committee Chair, United States
Lars Ingolf Eide, Norway

31. Update on Future CSLF Meetings *(5 minutes)*
Richard Lynch, CSLF Secretariat

32. Open Discussion and New Business *(10 minutes)*
Delegates

33. Summary of Meeting Outcomes *(5 minutes)*
Richard Lynch, CSLF Secretariat

34. Closing Remarks / Adjourn *(5 minutes)*
Åse Slagtern, Technical Group Chair, Norway

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Minutes of the Technical Group Meeting
Melbourne, Victoria, Australia
Wednesday, 17 October 2018

LIST OF ATTENDEES

Chair	Åse Slagtern (Norway)

Delegates

Australia:	Andrew Barrett (*Vice Chair*), Max Watson
Brazil:	Ana Musse
Canada:	Eddy Chui (*Vice Chair*), Mike Monea
China:	Ping Zhong
European Commission:	Jeroen Schuppers
France:	Didier Bonijoly
Italy:	Paolo Deiana, Sergio Persoglia
Japan:	Ryozo Tanaka, Yukihiro Kawaguchi, Takuro Okajima
Korea:	JaeGoo Shim, YiKyun Kwon
Norway:	Lars Ingolf Eide, Espen Bernhard Kjærgård
Saudi Arabia:	Amar Alshehri, Pieter Smeets
United Kingdom:	Brian Allison
United States:	Mark Ackiewicz, Sallie Greenberg

Representatives of Allied Organizations

CO_2GeoNet Association:	Sergio Persoglia
Global CCS Institute:	Alex Zapantis
IEAGHG:	Tim Dixon, Jasmin Kemper

CSLF Secretariat	Richard Lynch

Invited Speakers

Australia:	Jason Russo (*Department of Industry, Innovation and Science*)
	David Byers (*CO2CRC*)
	John Torkington (*Chevron Australia*)
	Kevin Dodds (*ANLEC R&D*)
	Ian Filby (*Victorian Department of Economic Development, Jobs, Transport and Resources*)
	Dominique Van Gent (*Western Australian Department of Mines, Industry Regulation and Safety*)
United Kingdom:	M. Pourkashanian (*University of Sheffield*)
United States:	Frank Morton (*National Carbon Capture Center*)

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Observers

Australia:	Sarah Chapman (*Department of Industry, Innovation and Science*) *
	Chamaka DeSilva (*Department of Industry, Innovation and Science*)
	Kingsley Omosigho (*Department of Industry, Innovation and Science*)
	Tim Sill (*Department of Industry, Innovation and Science*) *
Canada:	Kathryn Gagnon (*Natural Resources Canada*) *
	Beth Hardy (*International CCS Knowledge Centre*)
Japan:	Jiro Tanaka (*Japan CCS Company*)
Korea:	Mi Hwa Kim (*KETEP*)
Saudi Arabia:	Hamoud Alotaibi (*Ministry of Energy*) *
	Abdullah AlSarhan (*Ministry of Energy*) *
United States	Jarad Daniels (*Department of Energy*) *
	Katherine Romanak (*University of Texas*)

* Policy Group delegate

1. Chairman's Welcome and Opening Remarks

The Chair of the Technical Group, Åse Slagtern, called the meeting to order and welcomed CSLF delegates and stakeholders to Melbourne. Ms. Slagtern mentioned that this would be a busy meeting, with presentations on many topics of interest related to carbon capture and storage (CCS) including presentations by the International Test Center Network, meeting host CO2CRC, and three CSLF-recognized projects. Additionally, there would be updates from all of the Technical Group's task forces as well as the Technical Group's three allied organizations: the CO_2GeoNet Association, the Global CCS Institute (GCCSI), and the IEA Greenhouse Gas R&D Programme (IEAGHG). Ms. Slagtern also called attention to the downloadable documents book that had been prepared by the Secretariat for this meeting which contains documents relevant to items on the agenda.

2. Meeting Host's Welcome

Jason Russo, General Manager of Onshore Minerals at the Australian Government's Department of Industry, Innovation and Science, welcomed meeting attendees to Melbourne while acknowledging the traditional custodians of the land and paying respects to their elders – past, present and future. Mr. Russo then set the stage for the meeting by affirming Australia's overall commitment to CCS and by briefly describing some of its activities, from R&D being conducted by CO2CRC to large-scale projects such as the Gorgon Project. Mr. Russo closed his welcoming speech by also acknowledging the contributions over the past three years of the Technical Group Vice Chair and PIRT Chair Andrew Barrett, who was participating in his final CSLF meeting.

3. Introduction of Delegates

Technical Group delegates and stakeholders present for the meeting introduced themselves. Thirteen of the twenty-six CSLF Members were represented. Stakeholder observers from six countries were also present, as were representatives from the three allied organizations.

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4. **Adoption of Agenda**

The Agenda was adopted with no changes. (*Note: Subsequently, due to scheduling considerations for the presenter, the update from the CSLF-recognized Gorgon CO_2 Injection Project was moved forward in the agenda by one place*.)

5. **Approval of Minutes from April 2018 Meeting**

The Minutes from the April 2018 Technical Group Meeting were approved with no changes.

6. **Report from CSLF Secretariat**

Richard Lynch provided a report from the CSLF Secretariat which reviewed highlights from the April 2018 CSLF Technical Group Meeting in Venice, Italy. This was a two-day event, consisting of PIRT and Technical Group meetings, that was held just prior to the CO_2GeoNet Association's 2018 Open Forum. Presentations from both meetings are online at the CSLF website.

Mr. Lynch reported that there were several notable highlights and outcomes from the meeting:

- The Norcem Carbon Capture Project, sited in Norway, received a CSLF Global Achievement Award. (*Note: The project sponsor representative was not able to attend the meeting, so presentation of the award took place in Norway in May*.)
- The Enabling Onshore CO_2 Storage in Europe (ENOS) Project received PIRT and Technical Group approvals. (*Note: ENOS became a CSLF-recognized project following Policy Group approval at its October 2018 meeting in Melbourne*.)
- The Technical Group formed a new Task Force to examine non-Enhanced Oil Recovery (EOR) CO_2 utilization options, with a plan and timeline to be presented at the next Technical Group meeting. Task force members include the United States (Chair), Australia, Canada, France, the Netherlands, and Saudi Arabia.
- The Technical Group formed an ad hoc committee to follow up on recommendations from the CSLF Technology Roadmap (TRM). This committee will also attempt to gauge the use of Technical Group task force reports, and will align itself with the Policy Group's Academic Task Force and Communications Task Force. The United States is the Chair of this committee.
- The Bioenergy with CCS (BECCS) Task Force, chaired by the United States, issued its final report and has completed its activities.
- The Task Force on Hydrogen Production and CCS, chaired by Norway, has completed its preliminary "Phase 0" activities and will not continue further. Instead, a workshop on Hydrogen with CCS will be organized for a future CSLF meeting.
- The CCS for Energy Intensive Industries Task Force, chaired by France, and the Improved Pore Space Utilisation Task Force, co-chaired by Australia and the United Kingdom, will both present final reports at the next Technical Group meeting.
- The Technical Group will not form a new task force on CO_2 Capture by Mineralization, as it was deemed premature to do so.

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7. Update from the CO_2GeoNet Association

Sergio Persoglia, Secretary General of the CO_2GeoNet Association, gave a short presentation about the organization and its activities. CO_2GeoNet is a pan-European research association for advancing geological storage of CO_2. It was created as a European Union FP6 Network of Excellence in 2004 and transformed into an Association under French law in 2008. Dr. Persoglia stated that the overall mission of the CO_2GeoNet Association is to be the independent scientific voice of Europe on CO_2 geologic storage in order to build trust in the technologies involved and to support wide-scale CCS implementation. Membership comprises 29 research institutes from 21 countries, and CO_2GeoNet uses the multidisciplinary expertise of its members to advance the science supporting CCS. There are currently four categories of activities: joint research, scientific advice, training, and information / communication.

Dr. Persoglia then provided an update on recent activities of the organization. Since the April 2018 Technical Group meeting in Venice, the CO_2GeoNet Association has been involved in several diverse areas of activity. It has advised and monitored the actions on CCS and also carbon capture and utilization (CCU) in the European SET Plan; it has consulted on the Innovation Fund; it has been involved in developing standards for CCS/CCU via the ISO; it has developed position papers for use by policy-makers; and it is playing an active role (including organizing a side event on "Demystifying Negative Emission Technologies") in the roll-up to COP24. The CO_2GeoNet Association is also overseeing the ENOS project.

Dr. Persoglia concluded his presentation with a short update on its 13th Open Forum, which was held immediately following the CSLF Technical Group meeting in Venice. There were 116 registered attendees representing 27 countries; presentations, videos, and key messages are now online at the CO_2GeoNet website. The Open Forum included a knowledge-exchange workshop and two other workshops organized by the ENOS Project. There was also a meeting with journalists. Dr. Persoglia stated that the next Open Forum will be held next year in Venice on May 7-8, and that he hoped that many CSLF delegates will be able to attend.

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

Tim Dixon, Programme Manager for the IEAGHG, gave a presentation about the organization and its continuing collaboration with the CSLF's Technical Group. The IEAGHG was founded in 1991 as an independent technical organization with the mission to provide information about the role of technology in reducing greenhouse gas emissions from use of fossil fuels. Currently there are 33 Members from 15 countries plus OPEC, the European Union, and the IEA's Coal Industry Advisory Board (CIAB). These Members set the strategic direction and technical programme for the organization. The IEAGHG's 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 (320 reports published as of October 2018), the six international research networks about various topics related to CCS, and the biennial GHGT conferences (the next one in Melbourne during the week after the CSLF meeting). Other IEAGHG activities include its biennial post-combustion capture conferences, its annual International CCS Summer School, peer reviews with other organizations, activity in international regulatory organizations such as the UNFCCC, the

ISO TC265, and the London Convention, and collaboration with other organizations including the CSLF.

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 seven IEAGHG studies that originated from the CSLF Technical Group or related activities, including reports on three International Workshops on Offshore Geologic CO_2 Storage.

Mr. Dixon concluded his presentation with showing lists of reports recently published, reports in progress to be published, studies underway, studies awaiting start, and webinar series. Mr. Dixon also briefly described IEAGHG's research networks and other upcoming events.

9. Update from the Global CCS Institute

Alex Zapantis, General Manager – Commercial for the Global Carbon Capture and Storage Institute (GCCSI), gave a presentation about the organization. The GCCSI has recently reorganized on how it operates, having moved away from a regional structure toward more of a global outlook on CCS. The overall mission is still to accelerate the deployment and commercial viability of CCS globally, but the new functional structure starts with advocacy, which will lead to new policy towards CCS, which will lead to investment, which will result in deployment. The overall focus is on valued and impactful work which will expand and leverage the GCCSI's resources in the CCS community. Mr. Zapantis mentioned that services of the GCCSI include research on key aspects of CCS deployment (including publication of an annual "Global Status of CCS" document), advice and capacity building (through tailored workshops, conferences, and presentations to groups such as the CSLF), and communications / advocacy (to build awareness of CCS and its role in achieving climate targets and reducing emissions).

Mr. Zapantis stated that the GCCSI has been working extensively with its members. This has included drafting and launching the United Kingdom Carbon Capture, Utilization and Storage (CCUS) Cost Challenge Task Force report titled "Delivering Clean Growth", organizing GCCSI-led CCS forums in eight different cities around the world, organizing two CCS 'safaris' in Norway, and organizing a CCS side event with China at COP23. In closing, Mr. Zapantis briefly described the GCCSI's involvement in the upcoming global CCUS summit titled "Accelerating CCUS" which will be held in Edinburgh, Scotland, UK in late November.

10. Activities of CO2CRC Ltd.

David Byers, CEO of CO2CRC Ltd., gave a presentation about the organization and its activities. For more than a decade, CO2CRC has been at the forefront of demonstrating the scientific viability of CCS in Australia. It is the first company in Australia to have undertaken CCS end-to-end, from capture to storage, and its research is demonstrating CCS at pilot scale using novel technologies. To date, more than 80,000 tonnes of CO_2 have been injected, monitored, and safely stored in CO2CRC test programs. Mr. Byers stated that CO2CRC's strategic focus areas optimizing storage, reducing capture costs, enhancing CO_2 utilization, and collaboration & leadership. The first two are being investigated for validation at the Otway Research Facility, where low-cost and low-impact monitoring technologies, well integrity and leakage mitigation methodology, and durable membrane/adsorbent materials for CO_2 separation from mixed gas streams will be tested. CO2CRC is also providing expert advice on CCUS for government and industry, leveraging its technical proficiency and research track record. Its expertise is also being used to support Australian industry efforts to increase hydrocarbon recovery through CO_2-EOR and to investigate bio-refinery viability in an Australian context.

Concerning the CO2CRC Otway Research Facility, Mr. Byers stated that it is one of the most comprehensive CO_2 storage demonstration laboratories in the world, and is verifying the fundamental science of CO_2 storage in Australia while further validating injection, storage and monitoring technologies globally. The facility features a state-of-the-art seismic monitoring array for observing and benchmarking subsurface technologies and processes, and has produced and made available high quality, comprehensive datasets from its previous operations. The Otway Project, to date, consists of three stages. An initial stage, from 2004 to 2009, demonstrated safe transport, injection and storage of CO_2 into a depleted gas reservoir. The second stage, which started in 2009 and will conclude in 2019, has demonstrated safe injection of CO_2 into a saline formation. The third stage, which began in 2015 and will conclude in 2022, will develop and validate safe, reliable and cost-effective technologies for subsurface monitoring of stored CO_2. Additional stages of the project are anticipated, one of which will develop cost-effective, compact CO_2 separation technologies from mixed CO_2-natural gas streams, while another will improve the capability to predict the role of geologic faults in controlling CO_2 fluid flow in the near surface while improving near surface monitoring capabilities.

Mr. Byers closed his presentation by mentioning CO2CRC's role in an initiative to more closely examine what CO_2-EOR opportunities exist across Australia. This will include both research activities and reservoir characterizations to gauge EOR potential.

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

The PIRT Chair, Andrew Barrett, gave a short presentation that summarized the previous day's meeting, which was held in Warrnambool just prior to the site visit to the nearby CO2CRC Otway Research Facility. Mr. Barrett reported that the meeting featured a presentation by Max Watson about the Otway Facility, but the main topic on the agenda was a presentation by Sallie Greenberg about the Technical Group's ad hoc committee on task force maximization and knowledge sharing. An outcome from this agenda item was that it was deemed essential for the committee to continue its activities with no firm end date, as this will be one of the things that defines the overall worth of CSLF activities. An action resulting from the meeting was that whenever a task force completes a report, the PIRT should have an active role in dissemination of this news, via the CSLF Secretariat, in the form of an informational email of some sort to the overall CSLF mailing list. The CSLF's allied organizations will also be requested to pass this news on via their own mailing lists.

At the conclusion of Mr. Barrett's presentation it was noted that this is his final CSLF meeting due to impending retirement. In appreciation of his three years of service as PIRT Chair, he was presented (by the Technical Group Chair) a recognition award for his leadership of the PIRT.

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12. Report from the CCS for Energy Intensive Industries Task Force

Task Force Co-Chair Didier Bonijoly gave a brief update on the task force, which had been established at the October 2016 meeting in Tokyo with a mandate to investigate the opportunities and issues for CCS in the industrial sector and show what the role of CCS could be as a lower-carbon strategy for CO_2-emitting industries. The focus of the task force is to show how CCS in energy intensive industries will contribute to the double target of economic growth and climate change mitigation, with an objective to provide recommendations for technology developments that are needed to accelerate the deployment of CCS for these industries. Dr. Bonijoly reported that the task force consists of members from France's Club CO_2, with additional contribution from Canada, Germany, the Netherlands, Norway, Saudi Arabia, the United Arab Emirates, and the United States. The task force also has commitment from a wide range of professional and technical expertise in the industrial sector including oil and gas (both upstream and downstream), cement, steel, hydrogen, chemicals, fertilizer, and waste-to-energy.

Dr. Bonijoly then called on task force member Lars Ingolf Eide to summarize relevant issues being addressed. These include: why CCS for industry is an important issue, which industries and their emissions to focus on, what potential alternatives to CCS exist (if any) to achieve zero CO_2 emissions for different industries, and the status of CCUS developments from laboratory scale to industrial demonstration. The task force's final report will include short chapters on nine industrial sectors: steel, cement, waste-to-energy, fertilizers, hydrogen production, natural gas production, heavy oil production, chemicals, and refining. There will also be an annex with detailed papers for each of these sectors. Important conclusions from the task force's work are that:

- Some process CO_2 emissions by energy intensive industries may be difficult if not impossible to reduce without CCUS.
- The value of CCUS can be much higher than the costs.
- CCUS is costly and may present operational challenges: it needs incentives and creative business models to stimulate widespread large-scale implementation.
- CO_2 utilization options can provide many energy intensive industries a revenue stream to offset the high costs of carbon capture. However, the climate mitigation potential for some utilization approaches can be limited.
- RD&D must be accelerated to drive down CCUS costs.

Mr. Eide concluded the presentation by stating that the task force has completed most of its work and that draft versions of all chapters in its final report have been prepared, though they are at different levels of maturity. The task force was unfortunately not able to have the report completed in time for the current meeting, but does expect it to be finalized and launched in time for the next meeting.

13. Report from the Improved Pore Space Utilisation Task Force

Task Force Co-Chairs Brian Allison and Max Watson gave a brief update on the task force, which was established at the November 2015 meeting in Riyadh. Task force members include Australia and the United Kingdom (as co-chairs), France, Japan, Norway, the United Arab Emirates, and the IEAGHG. Mr. Allison stated that the purpose of the task force is to investigate the concept of improved utilisation of geological storage space resource to increase CO_2 storage capacity, review the current state of processes and technologies that enhance utilisation of the storage space, highlight key techniques that have recently emerged internationally, and provide a set of options for stakeholders to develop into their CO_2 storage projects.

Dr. Watson then provided a summary of the task force's focus and activities. With straightforward CO_2 injection, in particular when storing in 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, and the resulting large lateral spread of CO_2 requires costly monitoring relative to the volume stored. Being able to improve pore space utilisation may be very beneficial in terms of increased storage capacity, reduced monitoring costs, and increased ability for 'hub' style storage operations. There are five main improved pore space utilisation techniques: improved sweep efficiency techniques from the oil and gas sector; pressure management via active and passive relief wells and/or increased injection pressure; microbubble CO_2 injection; CO_2 saturated water injection and geothermal energy; and compositional, temperature and pressure swing injection. All of these have reasonably high potential, but their technology readiness levels have not yet risen to the point where large-scale tests are imminent.

Dr. Watson concluded the presentation by providing a timeline for the task force final report. Coordination and alignment with key contributors will occur in early November, and task force members will circulate the draft report within their countries and organizations by about the end of November. Following this review cycle, the finalized version of the report should be ready for launch during the first part of 2019, prior to the next Technical Group meeting.

14. Report from the Non-Enhanced Hydrocarbon Recovery (EHR) Utilization Options Task Force

Task Force Chair Mark Ackiewicz gave a brief update on the task force, which had been established at the April 2018 meeting in Venice. A previous task force related to this topic (which had then included EOR) had existed between 2011 and 2013 and had issued two reports before disbanding. Key messages from these two reports were that:

- There are many CO_2 utilization options.
- EOR is the most near-term utilization option.
- Non-EOR CO_2 utilization options are at varying degrees of commercial readiness and technical maturity.
- Early R&D or pilot-scale activities should focus on addressing techno-economic challenges, verifying performance, and supporting smaller-scale tests of first generation technologies and designs.
- More detailed technical, economic, and environmental analyses should be conducted.

Mr. Ackiewicz reported that following the disbanding of that task force there have been other kinds of activities on this topic, including incentives and policy changes of various kinds, and also reports by academia, government, and independent organizations. There have also been, and continue to be, conferences entirely focused on CO_2 utilization or having that topic for one or more sessions. And, to date, there has been one CSLF-recognized project on CO_2 utilization: the Carbon Capture and Utilization / CO_2 Network Project located in Jubail, Saudi Arabia and sponsored by SABIC. Mr. Ackiewicz stated that this new task force would not be a continuation of the previous one – its main goal is to add value and not re-invent. Initially, the new task force will check on the status of non-EHR CO_2 utilization by reviewing the reports, projects, conferences, activities, and projects of various kinds, and government initiatives that have occurred since the closure of the previous task force. The task force will then develop a set of recommendations which will be presented at the next Technical Group meeting. Mr. Ackiewicz closed his presentation by listing the members of the task force: the United States (Chair), Australia, Canada, France, the Netherlands, and Saudi Arabia. Following Mr. Ackiewicz's presentation, Brazil, China, and the IEAGHG also joined the task force.

15. Update on CSLF-recognized Project: Gorgon CO_2 Injection Project

John Torkington, Climate Change Team Manager Chevron Australia, gave a presentation about the CO_2 capture and storage aspects of the Gorgon Liquefied Natural Gas (LNG) Project, located off Australia's western coast approximately 1,300 kilometers north of Perth. The Gorgon Project is Australia's largest single resource development, with more than 50 trillion cubic feet of discovered natural gas resources – enough to supply a city the size of New York for 100 years. There are six equity partners for the project, with Chevron Australia holding the largest stake and also being the project operator. Natural gas is being extracted at the rate of approximately 15 million tons per year, with production of an additional 20,000 barrels of condensate per day. Much of the gas is being liquefied for export to markets in eastern Asia, while some of the gas is supplying a natural gas pipeline that provides Western Australia an equivalent of up to 300 terajoules per day for its energy needs.

Mr. Torkington stated that the natural gas being extracted contains significant amounts of CO_2 which will be separated, compressed, and transported by pipeline to one of three sites on Barrow Island, where it is injected more than two kilometers down into the Dupuy Formation. This geologic formation has sufficient storage capacity to contain all the CO_2 separated during the expected 40-year lifetime of the project. The overall CO_2 injection rate is 3.4 to 4 million tonnes per year, which makes the Gorgon CO_2 Injection Project the largest of its kind in the world. Mr. Torkington stated that Barrow Island is a world-class nature reserve and a large amount of project resources has been allocated, and more than 300 environmental procedures of various kinds have been developed, to retain that status. This includes a strict quarantine management system to prevent non-indigenous plant and animal species from entering the island's ecosystem. Mr. Torkington closed his presentation by describing some of the CCS aspects of the project, which are equally rigorous. These include an extensive integrated monitoring plan (which includes seismic monitoring and reservoir surveillance wells) to track movement of the underground CO_2 plume. These are essential for the CCS part of the project to achieve its overall objective, to demonstrate the safe commercial-scale application of CO_2 storage technologies at a scale not previously attempted.

16. Report on International Overview of CCU Symposium

Didier Bonijoly gave a short presentation about the International Overview of CCU Symposium, which was held in early July in Paris and sponsored by France's "Club CO_2", a working group which currently has 24 members representing research organizations, governmental entities, and industry. The one-day Symposium drew 150 attendees and had a program which included a plenary plus a workshop. The plenary included reviews of policies, key projects, and other initiatives of interest from eleven countries; the workshop was set up with four teams working on life cycle assessment (LCA) barriers for CO_2-to-fuels, chemicals, mineralization, and bioconversion, and one other team working on standardization. There were several lessons learned from the workshop, two of the most important being: Use LCA at the beginning of the development of technologies to screen opportunities and provide solutions. And: Assess two different references – the current, most available process/technology and an environmentally competitive solution even if it's not economically viable. Dr. Bonijoly closed his presentation by reporting several conclusions from the Symposium:

- CCUS plays a key role in global climate goals – 15% toward achieving the 2-degrees-C target and 32% toward achieving the less-than-2-degrees-C target.
- CO_2 utilization addresses political and public acceptance drawbacks of CCS.
- Many countries plan to support research and demonstration projects for CO_2 utilization in order to encourage new technologies.
- No CO_2 utilization options are currently available which meet the three criteria proposed by the International Energy Agency (IEA): emission reduction, economic viability, and market.
- CO_2 utilization and storage technologies must be developed and deployed in parallel, and not be perceived as competing with each other.
- Market insights for CO_2 utilization are promising, with the potential for converting more than 6 billion tonnes of CO_2 per year into useful products such as building materials, chemical intermediates, fuels, and polymers. However, significant progress toward scalable technologies is needed,

17. Activities of the Australia National Low Emissions Coal Research and Development (ANLEC R&D) Initiative

Kevin Dodds, General Manager for Research at ANLEC R&D, gave a presentation about the organization and its activities. ANLEC R&D is a partnership between the Australian Government and the Australian coal industry and has the goal of accelerating deployment of lower emission technology for coal-fired power stations in Australia. It was founded in 2010 and has deployed a research effort of more than A$200 million in more than 25 institutions throughout Australia. The current focus is to accelerate commercial deployment of CO_2 storage across three Australian geological basins.

Mr. Dodds provided several examples of large ANLEC R&D research and technology initiatives being pursued by Australian commercial-scale projects: For the Callide Oxyfuel Project in southwestern Australia, a study determined that low-cost desulfurization is viable and that separate NOx removal and mercury capture are not required. A Gippsland Basin marine monitoring activity performed an assessment of shallow-focused marine monitoring technologies for sub-seabed CO_2 storage in southeastern Australia, while also developing and verifying an atmospheric assurance system for the Gippsland near-shore environment. For the Surat Basin in eastern Australia, a project co-funded by ANLEC R&D has been established to demonstrate the viability of CCS which will result in a both a feasibility study and a front end engineering design (FEED) study.

18. Update on the China Australia Geological Storage of CO_2 (CAGS) Project

Andrew Barrett, General Manager of Energy Systems at Geoscience Australia, gave a short presentation about the CAGS project, a bilateral activity between China and Australia that is jointly managed by Geoscience Australia and the Administrative Centre for China's Agenda 21. The overall focus is on capacity building in China and Australia for geological storage of CO_2. Mr. Barrett stated that project activities have included capacity building for Chinese researchers and central government officials at a national level and scientific exchanges involving mostly junior Chinese academics. The Australian government has also funded research projects in China.

Mr. Barrett highlighted one of the recent CAGS capacity building activities, a workshop and CCS school in China's Xinjiang Province in 2017. It was the first bilingual conference on CCS in that part of China and brought Australian and international expertise to the region. The outcome was the launch of the Xinjiang CCUS Research Centre at the workshop. Other activities in the current phase of the CAGS Project include integrated monitoring research of a CO_2-EOR demonstration project at Yanchang oilfield, an assessment of potential CO_2 geological storage in China's Junggar Basin, and a feasibility study of the Xinjiang Guanghui CCUS Pilot Project. Mr. Barrett closed his presentation by providing examples on how the CAGS Project is leveraging further investment, and how the project has increased collaboration through its exchange program. These will all be of benefit to several large pilot projects that are already underway in China and to seven large-scale CCUS projects (two of which are in Xinjiang) that are in the planning stage. Mr. Barrett also stated that because of the CAGS Project, CCUS is also gaining new momentum in Australia.

19. Update from CSLF-recognized Project: CarbonNet Project

Ian Filby, the CarbonNet Project Director for the Victorian Department of Economic Development, Jobs, Transport and Resources, gave a short presentation about the CarbonNet Project, located in southeastern Australia. This project is investigating the feasibility for a large-scale multi-user CO_2 capture, transport and storage network in the Latrobe Valley and nearby areas including the offshore Gippsland Basin. It has been jointly funded by the Australian and Victorian governments and has had a significant research investment from organizations such as ANLEC R&D. The lead research organization for CarbonNet is CO2CRC, while the GCCSI is handling knowledge sharing aspects of the project.

Mr. Filby stated that the Victorian State Government, in 2017, issued a policy statement on the future use of brown coal which supports CCS – it acknowledges strong interest in new industries for low emission, high value products from coal (e.g., hydrogen and fertilizers) and identifies opportunities for new coal-based projects that could utilize CCS. And it also commits to completing the CarbonNet Project. Mr. Filby reported several outcomes from a feasibility and commercial definition study which was recently completed: Geological storage site selection has certified a portfolio of three sites including a prioritized site. Feasibility studies across the full CCS chain have been done, as well as environmental risk assessment for air and groundwater potential impacts. A risk-adjusted whole of life costings for CO_2 transport and storage has been determined, and there have been market soundings with industry which have resulted in understanding of the preconditions for potential investors. Finally, a regulatory framework review has been done and a resulting regulatory fix plan is being implemented. Next steps include storage site appraisal activities and creation of a monitoring network, as well as stakeholder and community engagement. Mr. Filby closed his presentation by briefly describing the project's commercialization pathway, which includes implementation of supportive policies by government, completion of storage site appraisal, and obtaining investment by industrial customers and CCS service providers.

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20. Update from CSLF-recognized Project: South West Hub Project

Dominique Van Gent, Carbon Strategy Coordinator for the Western Australian Department of Mines, Industry Regulation and Safety, gave a short presentation about the South West Hub Project, located in southwestern Australia. This project has an eventual goal of implementing a large-scale CO_2 hub for multi-user capture, transport, and storage, where several industrial and utility point sources of CO_2 would be connected via pipeline to a geologic storage site. Mr. Van Gent stated that the area of Western Australia along the Indian Ocean coast south of Perth and north of the city of Collie is the heart of industry in the region and has CO_2 emissions of approximately 25 million tonnes per year. Screening studies conducted between 1998 and 2007 have identified a potential storage site near Collie and since then there has been extensive modeling and reservoir characterization activities. These have provided the information that the site can accept injection rates of at least 800,000 tonnes of CO_2 per year for more than 30 years, and the underground CO_2 plume will remain contained for at least 1,000 years. All this can be achieved through a well count of nine or less. Mr. Van Gent provided that it may even be possible to store much higher volumes, as injection rates of 3 million tonnes per year for 30 years have been modeled. If this proves feasible, then the South West Hub could be a sequestration site for CO_2 produced throughout the eastern Asia region.

Mr. Van Gent concluded his presentation by stating that the project has several needs if it is to progress further: There is a need for continued Government support as there is currently no business imperative. There is a need for industry to voice its support for CCS technologies as they pursue decarbonization. And there is a need to develop a narrative for the community about the overall worth and safety of CCS. For that last need, Mr. Van Gent stated that the only way to build confidence with the public is through a well-planned demonstration.

21. Update from the Mission Innovation Carbon Capture Innovation Challenge

Brian Allison, Assistant Head CCUS R&D and Innovation at the United Kingdom's Department for Business, Energy and Industrial Strategy and Co-Lead for Mission Innovation’s Carbon Capture Innovation Challenge (CCIC), gave a short presentation about Mission Innovation and its CCIC. Mission Innovation is a multilateral Ministerial-level initiative that was launched in November 2015 with the overall goal of accelerating the pace of clean energy innovation, to achieve performance breakthroughs and cost reductions in order to provide widely affordable and reliable clean energy solutions. Mission Innovation seeks to double cumulative Mission Innovation countries’ investment in clean energy (from $15 billion to $30 billion) over five years (from 2016 to 2021), to increase private sector engagement in clean energy innovation, and to improve information sharing among Mission Innovation countries.

Mr. Allison stated that currently there are twenty Mission Innovation countries that are participating in the CCIC. The overall objective is to enable near-zero CO_2 emissions from power plants and carbon intensive industries. This would involve identifying and prioritizing breakthrough CCUS technologies, developing pathways to close RD&D gaps, recommending multilateral collaboration mechanisms, and driving down the cost of CCUS through innovation. The overall work plan includes organizing CCUS Experts Workshops, engaging stakeholders (both industry and NGOs), and building multilateral collaboration mechanisms. To that end, a CCUS Experts Workshop, co-chaired by the United States and Saudi Arabia, was held in 2017 and focused on establishing the current state of technology in CCUS, identifying and prioritizing R&D gaps and opportunities, and establishing high priority research directions to address opportunities. Mr. Allison stated that the Workshop was a success, with 22 countries participating and a total of 257 participants representing government, academia, and industry. There were three main focus areas: CO_2 capture, CO_2 utilization, and CO_2 storage. In addition to these, a separate group was focusing on crosscutting issues. Each of these focal areas developed a set of international agreed priority research directions (PRDs), which were summarized in the report "Accelerating Breakthrough Innovation in Carbon Capture, Utilization, and Storage" dated September 2017. Mr. Allison stated that the PRDs are not meant to be prescriptive and all-inclusive. Instead, they were designed to inspire the CCUS research community to elucidate and illuminate the science that underpins CCUS. Mr. Allison concluded his presentation by providing the next steps for the CCIC. These include creating an action plan, developing collaboration mechanisms, and fostering engagement with industry and other multilateral CCUS initiatives, including the CSLF.

22. Report on 3rd International Workshop on Offshore Geologic CO_2 Storage

Tim Dixon gave a short presentation about the continuing series of workshops, co-sponsored by the IEAGHG, about offshore geologic storage of CO_2. This third in the series, hosted by the Research Council of Norway in early May, addressed and built on recommendations and topics raised by the first two workshops (which were held in 2016 and 2017, respectively), and continued the theme of "how to do". Mr. Dixon stated the series of workshops originated following the 6th CSLF Ministerial (in 2015), where one of the messages to Ministers was that even though there is a growing wealth of research, development and practical experiences concerning offshore CO_2 geologic storage, this expertise is familiar to only a few specific countries. There are other countries with offshore storage potential which are not yet pursuing these technologies and could benefit from knowledge sharing.

Mr. Dixon reported that the scope of this 3rd workshop was very broad and included sub-themes such as value chains for offshore storage, re-use of existing infrastructure, monitoring offshore CO_2 storage and EOR, offshore CO_2 resource assessment, standards and regulatory frameworks, updates from current projects, and brainstorming toward an international collaborative project. Mr. Dixon described each of these in detail, and then closed his presentation with a list of recommendations resulting from the workshop. These included:

- Explore models for a proposed international collaboration project.
- Consider how to build knowledge sharing from hands-on operational projects (including a proposed international collaboration project).
- Provide a roadmap to existing information sources about offshore storage.
- Determine which developing countries would be attracted to offshore storage.
- Identify key people in those developing countries and find mechanisms for bringing them to workshops and other conferences themed on offshore storage. Advocacy toward funders of CCS is needed.

23. Update on International Test Center Network (ITCN)

Frank Morton, Director of Technology at the National Carbon Capture Center (NCCC) in the United States, and Prof. M. Pourkashanian of the University of Sheffield in the United Kingdom, gave a short presentation about the ITCN and its collaborative activities. Mr. Morton stated that the ITCN was launched in 2013 to accelerate CCS technology development. Its main function is to facilitate knowledge sharing of operational experience and non-confidential information for CO_2 capture technologies, in terms of facility operations, facility funding, safety, and analytical techniques. Among the objectives of the ITCN are increasing insight and awareness of different technologies that may reduce risks and increase investments in CO_2 capture technologies and enhancing public awareness and acceptance of the technologies involved. The ITCN will also work with technology developers as appropriate on scale-up testing of their technologies. Among the benefits of ITCN membership are online access to the ITCN Handbook, online access to ITCN Facilities database, and online access to the ITCN community via the Members' Exchange facility. There are currently thirteen ITCN members which global represent four continents.

Mr. Morton welcomed the ongoing ITCN partnership with the CSLF Technical Group, stating that it was willing to be part of future Technical Group activities concerning CO_2 capture. Prof. Pourkashanian closed the presentation by describing several possible kinds of future collaboration between the ITCN and the Technical Group. These include evaluation of CO_2-containing flue gas from natural gas combustion and trying to find ways to support model development and advanced simulations with a focus on reducing capital costs / operating expenses.

Following the presentation, ensuing discussion reinforced the overall worth of collaboration between the ITCN and the Technical Group. Lars Ingolf Eide stated that such cooperation will be very useful to Technical Group task forces and toward future updates of the TRM. Mike Monea complimented the ITCN on its willingness to share information. Mark Ackiewicz stated that one thing that would really be of help to the Technical Group would be the ITCN providing information on any recurring specific challenges that need to be addressed for specific CO_2 capture technologies. In response, Mr. Morton stated that the ITCN would provide the Technical Group a list of such recurring issues.

24. Preview of CSLF Presentation at GHGT14

Lars Ingolf Eide provided a preview of the "Recent Activities of the Technical Group of the Carbon Sequestration Leadership Forum" presentation that was scheduled for the following week at the GHGT14 conference. The presentation provided brief overviews of the CSLF's overall objectives, organization structure, and current activities. The presentation also described the benefits for projects seeking CSLF recognition (to both the project sponsors and the CSLF) and the TRM and its recommendations. At the close of the presentation there were several slides which provided information about the current Ad Hoc Committee for Task Force Maximization and Knowledge Sharing Assessment including future plans and the way forward for this activity.

25. Report from the Ad Hoc Committee for Task Force Maximization and Knowledge Sharing

Committee Chair Sallie Greenberg made a presentation which in part recapped her previous day's presentation on this topic at the PIRT meeting. During the April 2018 Technical Group meeting in Venice, there was consensus of a need to measure progress on technical recommendations from the 2017 TRM and also to assess the impact and usage of task force reports. Dr. Greenberg reported that, following the Venice meeting, a small ad hoc group came together for this purpose and during the middle of 2018 conducted a survey to gather details on how TRM and task force reports were being used. In the months following that meeting, this group was formalized as the Ad Hoc

Committee for Task Force Maximization and Knowledge Sharing. During that time the Ad Hoc Committee drafted a white paper which briefly described its four main areas of examination:

- Task Force utilization analysis;
- TRM recommendation analysis and creation of baseline for future tracking;
- Knowledge sharing recommendations for dissemination; and
- Potential alignment of Task Forces with Technical and Policy Group activities within the CSLF (Academic, Communication, other), and also with outside organizations (IEAGHG, CCS Knowledge Center, CO_2GeoNet) and platforms (Mission Innovation, Clean Energy Ministerial, ACT).

Dr. Greenberg stated that the Ad Hoc Committee conducted a survey of Technical Group delegates prior to the current meeting to gather details on how the TRM and task force reports are being used and by whom as a first step in establishing a baseline for understanding TRM monitoring. Although more work is needed, responses received indicated that the majority of respondents have read and used the TRM. Further, web statistics indicate that the TRM is the second-most downloaded document (after the CSLF Charter) if documents supporting CSLF meetings are excluded. Responses to the survey also indicated that there were three main types of TRM usage: to help define important topics relevant to CCUS, for developing national CCUS strategies and reports of various kinds, and as background information for developing specific RD&D strategies and proposals.

There was also useful information from the survey about usage of task force reports. The most widely-used reports are those which focus on CO_2 capture technologies, hydrogen with CCS, offshore CO_2 storage, and CO_2 utilization through enhanced oil recovery (EOR). These reports have been most often used for knowledge and technical gain, RD&D program planning, and (by the ISO TC265 committee) in developing standards. Additional usages have been for technology assessment, strategic planning, and proposal development. Dr. Greenberg stated that more than 50% of the survey respondents reported that task force reports have been used in decision making, policy making, or in knowledge sharing forums.

In concluding, Dr. Greenberg provided some suggestions for future Technical Group activities, based in part on information gleaned from the survey. It identified that there was an obvious need to track TRM technology recommendations, which will be an ongoing priority of the ad hoc committee, but beyond that the survey indicated there appear to be several areas where activities are warranted. These include:

- Hub/infrastructure;
- Support of developing countries (*note: this was approved by the CSLF's Capacity Building Task Force in its meeting which immediately followed the Technical Group meeting*);
- Cost-effective capture technologies;
- More clarity on economic benefits of low-carbon policy; and
- Providing technical inputs into any business model and socio-economic benefits discussions.

Dr. Greenberg stated that a future workshop on hub/infrastructure would be an especially worthwhile activity, especially if it resulted in a report as a deliverable. Also, better knowledge sharing of all Technical Group results is imperative, and the

Technical Group should find better methods for wider distribution of its reports, especially the TRM.

In the ensuing discussion, Lars Ingolf Eide complimented the Ad Hoc Committee's work by stating that responses concerning the need for improved infrastructure provided insight for possible future Technical Group activities such as a Hub and Infrastructure task force. Mark Ackiewicz agreed and stated that the Technical Group's allied organizations can play a role in various ways, for instance in co-sponsoring technical workshops. Sergio Persoglia, speaking for the CO_2GeoNet Association, expressed an interest in helping to organize targeted workshops that could relate directly back to technical recommendations from the TRM or from task forces. Tim Dixon, speaking for the IEAGHG, agreed but stated that any such cooperative activities needs to be beneficial to the allied organization as well as the Technical Group. Åse Slagtern suggested that a good working mode going forward for collaborating with allied organizations would be to jointly produce overview reports, hold workshops, and engage in other similar activities, and that the Ad Hoc Committee could work out specific details. There was consensus for adopting that approach and also that the Ad Hoc Committee should continue its activities for the foreseeable future, as this is a very important Technical Group function.

26. Possible New Technical Group Activities

Technical Group Chair Åse Slagtern made a short presentation that summarized existing Technical Group activities and possible new ones. There are now four active task forces (or equivalent) besides the PIRT: Improved Pore Space Utilization (co-chaired by Australia and the United Kingdom, active since 2015), CCS for Energy Intensive Industries (chaired by France, active since 2016). Non-EHR Utilization Options (chaired by the United States, formed at the Venice Technical Group meeting), and the Ad Hoc Committee (chaired by the United States, formed following the Venice Technical Group meeting). Ms. Slagtern stated that there are many other potential new topics that had been identified by a previous Technical Group working group. Two that were ranked with a high priority are "Hydrogen with CCS" and "CO_2 Hubs and Infrastructure". Concerning Hydrogen with CCS, Ms. Slagtern noted that a Task Force had formed for a preliminary "Phase 0" but had concluded that it would be better to have a workshop on this topic than to continue the task force. The IEAGHG and the CSLF's Norway delegation have been asked to take the lead in planning the workshop. Ms. Slagtern concluded her presentation by stating that there was not yet any Technical Group activities concerning CO_2 Hubs and Infrastructure.

Ensuing discussion resulted in formation of a new Hub and Infrastructure Task Force. However, this task force will conduct only preliminary "Phase 0" activities to review what has previously been done (e.g., reports and conference presentations) on the topic. The task force will present a recommendation on whether or not to continue past this preliminary phase at the next Technical Group meeting. Task force members for the preliminary phase are Norway (lead), Australia, Brazil, Canada, and the United Kingdom

27. Update on Future CSLF Meetings

Richard Lynch reported that the 2019 Mid-Year Technical Group meeting would be held in Champaign, Illinois, USA, and called on Sallie Greenberg to provide additional information. Dr. Greenberg stated that the date would be in April the week following Easter, and would be held in conjunction with the Annual Meeting of the Midwest

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Geological Sequestration Consortium (MGSC) which will be open to CSLF meeting attendees. More details will be forthcoming soon.

28. Open Discussion and New Business

There was no new business and no other announcements.

29. Election of Technical Group Officers

Richard Lynch presided over this item of the agenda. Mr. Lynch stated that according to the CSLF Terms of Reference and Procedures, CSLF Chairs and Vice Chairs are elected every three years. The previous election for the Technical Group was in 2015 at the CSLF Ministerial Meeting in Riyadh, Saudi Arabia.

By consensus, Norway was re-elected as Chair. Australia and Canada were re-elected as Vice Chairs. Japan was elected as Vice Chair, replacing South Africa.

30. Closing Remarks / Adjourn

Technical Group Chair Åse Slagtern thanked the delegation from Australia for hosting the meeting, CO2CRC Ltd. for arranging the field trip to the Otway Research Facility, the Secretariat for its pre- and post-meeting support, and the delegates and invited speakers for their active participation. She then adjourned the meeting.

Summary of Meeting Outcomes

- Norway was re-elected as Technical Group Chair. Australia and Canada were re-elected as Technical Group Vice Chairs. Japan was elected as Technical Group Vice Chair, replacing South Africa.
- The CCS for Energy Intensive Industries Task Force and the Improved Pore Space Utilisation Task Force will present their final reports at the next Technical Group meeting.
- The Non-EHR Utilization Options Task Force will present a set of recommendations at the next Technical Group meeting. New task force members are Brazil, China, and the IEAGHG.
- A new Hub and Infrastructure Task Force was formed to conduct initial "Phase 0" activities to review what has previously been done (e.g., reports and conference presentations) on the topic. The task force will present a recommendation on whether or not to continue past this preliminary phase at the next Technical Group meeting. Task force members for the preliminary phase are Norway (lead), Australia, Brazil, Canada, and the United Kingdom.
- The Ad Hoc Committee for Task Force Maximization and Knowledge Sharing will continue its activities for the foreseeable future, as this is a very important Technical Group function. A priority item will be to develop a methodology on how to measure any global progress in implementing TRM technical recommendations.
- A general working mode going forward for collaborating with allied organizations will be to jointly produce overview reports, hold workshops, and engage in other similar activities. Practical implementation will be worked out by the Ad Hoc Committee.
- The ITCN will provide the Technical Group a list of recurring specific challenges that need to be addressed for specific CO_2 capture technologies.

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- The IEAGHG and Norway's Technical Group delegation have been given the lead to plan a joint CSLF-IEAGHG workshop themed on Hydrogen with CCS.
- The next Technical Group meeting will be held in Champaign, Illinois, USA in April 2019, and would be held in conjunction with the Annual Meeting of the Midwest Geological Sequestration Consortium (MGSC) which will be open to CSLF meeting attendees.

TECHNICAL GROUP

Action Plan Status

Background

This paper, prepared by the CSLF Secretariat, is a brief summary of the Technical Group's current actions, potential actions that have so far been deferred, and completed actions over the past several years.

Action Requested

The Technical Group is requested to review the Secretariat's status summary of Technical Group actions.

Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF Technical Group Action Plan Status

(as of March 2019)

<u>Current Actions</u>

- CCS for Energy Intensive Industries *(Task Force chair: France)* [*Task Force formed in 2016*]
- Non-EHR CO_2 Utilization Options (*Task Force chair: United States*) [*Task Force formed in 2018*]
- Ad Hoc Committee for Task Force Maximization and Knowledge Sharing Assessment (*Committee chair: United States*) [*Committee formed in 2018*]
- Hub and Infrastructure Task Force *(Task Force chair: Norway)* [*Task Force formed in 2018; initial "Phase 0" activities to review existing reports and presentations in this area and then make recommendation on whether task force should be continued.*]

<u>Potential Actions</u>

- Geo-steering and Pressure Management Techniques and Applications [*Note: Geo-Steering was incorporated into Improved Pore Space Utilisation Task Force activities.*]
- Advanced Manufacturing Techniques for CCS Technologies
- Dilute Stream / Direct Air Capture of CO_2
- Global Residual Oil Zone (ROZ) Analysis and Potential for Combined CO_2 Storage and EOR
- Study / Report on Environmental Analysis Projects throughout the World
- Update on Non-EOR CO_2 Utilization Options
- Ship Transport of CO_2
- Investigation into Inconsistencies in Definitions and Technology Classifications
- Compact CCS
- Reviewing Best Practices and Standards for Geologic Monitoring and Storage of CO_2 *
- CO_2 Capture by Mineralization * [*Note: Action on this item has been indefinitely deferred.*]
- Global Scaling of CCS *

* *Received a high prioritization score from Working Group on Evaluating Existing and New Ideas for Possible Future Technical Group Actions.*

<u>Completed Actions (*since 2013*)</u>

- Improved Pore Space Utilisation (*Final Report expected in April 2019*)
- Hydrogen with CCS *(Final Report in June 2018)* [*Note: Task Force was discontinued after initial "Phase 0" research and literature review activities.*]
- Bio-energy with CCS (*Final Report in April 2018*)
- Offshore CO_2-EOR (*Final Report in December 2017*)
- Supporting Development of 2nd and 3rd Generation Carbon Capture Technologies (*Final Report in December 2015*)
- Technical Barriers and R&D Opportunities for Offshore Sub-Seabed CO_2 Storage (*Final Report in September 2015*)
- Review of CO_2 Storage Efficiency in Deep Saline Aquifers (*Final Report in June 2015*)
- Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2 (*Final Report in November 2014*)
- CCS Technology Opportunities and Gaps (*Final Report in October 2013*)
- CO_2 Utilization Options (*Final Report in October 2013*)
- Technical Challenges for Conversion of CO_2-EOR Projects to CO_2 Storage Projects (*Final Report in September 2013*)

CARBON SEQUESTRATION LEADERSHIP FORUM (CSLF)

TECHNICAL GROUP

TASK FORCE ON

IMPROVED PORE SPACE UTILISATION

Improved Pore Space Utilisation: Current Status of Techniques

APRIL 2019

Executive Summary

At the 2015 CSLF Ministerial Meeting in Riyadh, Saudi Arabia, a Task Force was formed to investigate Improved Pore Space Utilisation. The Task Force mandate was to investigate the current status of techniques that have the potential to improve how well the capacity of reservoirs for CO_2 storage are utilised. This document is a summary of this investigation.

This investigation represents a review of the current status and potential for various technologies to improve Pore Space Utilisation and does not necessarily represent the views of individual contributors or their respective employers.

For CCS to achieve the required contribution to the Paris Agreement's aim to keep the global temperature increase from anthropogenic carbon dioxide (CO_2) emissions to 2°C or below, the annual CO_2 storage rate needs to increase dramatically (from < 40 in 2018 to 2,400 million tonnes per annum storage by 2035). Internationally, this requires a significant increase in CCS infrastructure development, as recommended in the CSLF Technology Roadmap (2017a). Present progress towards CCS infrastructure is not on target, and strong actions are required to rectify this.

Better utilisation of 'investment ready' storage resources and 'discovered' resources is recommended to potentially improve the path towards the 2035 target, and broadly to significantly improve the economics of the CCS projects.

The pore space of a CO_2 storage system is the 'resource' to a CO_2 storage site operator. Presently, the efficiency of the storage resource is quite low, with only 1 to 4% of the bulk volume being utilised to store CO_2 in saline formations. A poor utilisation of this pore space resource means that the resource is wasted, and the opportunity to reduce the cost per tonne of CO_2 stored is significantly hindered. Conversely, a resource that is effectively utilised is likely to significantly improve the economics of CCS projects.

From a non-technical basis, the issue of effective storage space utilisation, including when competing subsurface uses exists, has been reviewed. While jurisdictions managing CO_2 storage on this first-come first-serve basis has short to medium term sustainability, competition for the pore space is likely to become an issue as CCS matures. A strategically managed approach is recommended in certain scenarios of future CO_2 storage, particularly for regions with multiple or connected storage options. To ensure effective utilisation of the pore space resource, a degree of pre-competitive characterisation would also be required including a detailed techno-economic evaluation of the storage region. This evaluation would include injection rate, cost, risk minimisation, multi-resources and would need to be considered within the framework of government energy policies.

This task force has included a review of mature capabilities from the petroleum sector in improving hydrocarbon sweep efficiency, including enhanced oil recovery techniques. This review found strong applicability in the use of foams as physical barriers in high permeability streaks to encourage better vertical sweep, and potential also for the application of polymers and surfactants to modify flow properties in CO_2 storage.

Four evolving technologies were reviewed as potential methods for improving the utilisation of pore space associated with CO_2 storage:

1. Pressure Management
2. Microbubble CO_2 Injection
3. CO_2 Saturated Water Injection & Geothermal Energy
4. Swing Injection

Combined with existing petroleum sector techniques, these technologies were reviewed in terms of prior R&D and application, technical readiness for commercial deployment, and the prospectively of the technology in improving pore space utilisation. All technologies reviewed represent strong value to the optimisation of site storage operations, yet many of them require further technical development before they could be deployed at scale commercially. A recommended action for the technology development is given for each technology.

Comparison table of pore space utilisation technologies. Technologies are ranked in order of priority (column 'P') for continued technology maturation. Green indicates high perspectivity for the technology, light green less urgency, while orange indicates lower technology prospectively broadly, yet strong niche opportunity.

P	Technology Type	Prior R&D and application	Technology Readiness Level (TRL)	Technology Prospectively
1	Microbubble CO_2 Injection	Laboratory and Modelled, prototype	TRL 4	High potential
2	Swing Injection	Laboratory and Modelled	TRL 3	High potential
3	Increased Injection Pressure	Laboratory and Modelled	TRL 3	High potential
4	Active Pressure Relief (increase sweep & reduce lateral spread)	Enhanced Oil Recovery (EOR), planned for Gorgon CO_2 injection project	TRL 6	High potential
5	Foams (block high permeability pathways)	EOR	TRL 6	Reasonably well understood
6	Passive Pressure Relief	Modelled	TRL 4	Limited effectiveness
7	Polymers (increase formation water viscosity)	EOR	TRL 7	Reasonably well understood
8	Surfactants (reduce residual saturation of formation water)	EOR	TRL 7	Reasonably well understood
9	CO_2 saturated water injection & geothermal energy	Laboratory and Modelled	TRL 3	Site specific & lower volume

* minor modelling and laboratory investigations may be required prior to commercial scale application

Contents

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This report was prepared for the CSLF Technical Group by the participants in the Improved Pore Space Utilisation Task Force:

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1 Introduction

The priority recommendation of the CSLF Technology Roadmap (2017a) is for CCS to have achieved a storage rate of at least 2,400 Mt of CO_2 per year by 2035, to ensure that CCS contributes its share to the Paris Agreement's aim to keep the global temperature increase from anthropogenic carbon dioxide (CO_2) emissions to 2°C or below.

18 large-scale CO_2 geological storage projects are presently in operation internationally, with a further five under construction, and 20 in various stages of development (Global CCS Institute, 2018). Together these facilities are storing almost 40 million tonnes (Mt) of CO_2 per year. These CO_2 injection projects include storage into saline formations for permanent storage including the Sleipner, Quest, Illinois Industrial CCS, and Snøhvit projects; and into producing oil fields for CO_2- enhanced oil recovery (EOR), including the Weyburn, Abu Dhabi CCS, and Petra Nova projects (source: Global CCS Institute).

These CO_2 storage projects have proven very effective in the safe storage of commercial quantities of CO_2. Presently however, these saline formation storage projects do not approach the technical storage capacity limit, nor do they have the onus to increase the rate of storage. Further, oil produced from CO_2-EOR projects carries a CO_2 footprint of 0.43 t CO_2 per barrel, in effect reducing the net CO_2 pore space utilisation (EPA, 2016). Technical solutions do exist to maximise CO_2 storage in an advanced CO_2-EOR operation so that net negative CO_2 emissions (Lipponen, 2015), yet this approach presently lacks a strong economic case to do so commercially.

For CCS to achieve the required targets for the Paris Agreement's aim, the annual net volume of CO_2 storage and abatement needs to increase dramatically (~60-fold by 2035). This will require many new commercial scale storage projects, and there are a number of efforts internationally to bring new CCS projects on line. In addition, being able to improve the utilised storage capacity of these new (and existing) projects could significantly improve the economics of the CCS projects.

1.1 Background

Initial "raison d'etre" as Presented to CSLF Ministerial Meeting

With straightforward CO_2 injection, in particular when storing in saline formations, a large portion of available pore space in a geological storage site is bypassed, or storage rate is limited by pressure build up. Utilised 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 for saline formations), and in many cases a resulting large lateral spread of CO_2 requires costly monitoring relative to the volume stored. Being able to improve pore space *utilisation may be very beneficial in terms of increased storage capacity, reduced monitoring costs, and increased ability for 'hub[1]' style storage operations.*

The pore space of a CO_2 storage system is the 'resource' to a CO_2 storage site operator. A poor utilisation of this pore space resource means that the resource is wasted, and the opportunity to reduce the cost per tonne of CO_2 stored is significantly hindered.

Typically, CO_2 injected into saline formations will rapidly migrate to the top of the reservoir unit due to buoyancy, and then migrate laterally, following dip along the base of the primary seal. The bulk of the reservoir rock's pore space is bypassed due to the rapid buoyant rise of the CO_2. Projects such as Sleipner, designed in a similar manner to hydrocarbon production in its early years (i.e. without significant integrated reservoir management techniques) show this effect. In this project, only a small fraction of the available pore volume in these storage sites is utilised for CO_2 storage due to both buoyancy and uneven CO_2 distribution due to "fingering" where large areas have not been penetrated by CO_2 at all.

Added to this is the large areal extent of the CO_2 plume, as volumetrically the CO_2 plume would be thin yet have a wide areal extent. A large areal extent could in some circumstances increase the probability of leaks along intersecting faults, abandoned wells, and other permeable zones in the seal. Therefore, pre-injection appraisal will need to be more extensive and monitoring strategies must cover large areas.

Much effort has been spent by the technical CCS community in improving the estimation of storage resource. These have resulted in publications providing methodologies for the estimation of storage resource of CO_2 in saline aquifers, hydrocarbon reservoirs and coal seams. These include the 'Methodology for Development of Carbon Sequestration Capacity Estimates' prepared for the National Energy Technology Laboratory, U.S. Department of Energy (US DOE, 2006), and the 'Estimation of CO_2 Storage Capacity in Geological Media – Phase II' prepared for the Carbon Sequestration Leadership Forum (CSLF, 2007). These two methodologies have since been compared by CSLF (CSLF, 2008) and by the CO2CRC Ltd. in 2008 (CO2CRC, 2008). Recently the Society of Petroleum Engineers (SPE) has addressed inconsistency with the development of a Storage Resource Management System (SRMS), improving the confidence regarding pore space resource assessments for CO_2 storage. The SRMS was applied to regional storage assessments for North America, the UK, Norway, China, Brazil, Australia and the Indian Subcontinent, to re-assess CO_2 storage capacity estimates. Of the 12,000 gigatonne total storage resource, enough work has been completed to mature only ~750 MT into 'investment ready' storage resources.

These studies have led to significantly improved global storage estimates and highlight two very important facts:

1. 'Investment ready' storage resources, whilst currently an order of magnitude higher than present day storage rates, are small relative to the target storage rate of 2,400 MT by 2035. Effort is required to increase the 'Investment ready' storage resource.

[1] Hub – A single storage location where CO_2 is transported from a range of different CO_2 sources.

2. Utilisation, or storage efficiency, into the existing 'Investment ready' storage resource must be optimal.

Presently, storage efficiency, the proportion of pore space utilised, is very low. In the case of saline formations (with a 15 to 85% confidence), CO_2 storage efficiency represents between 1 to 4% of the bulk volume. Storage efficiency is higher in depleted petroleum fields, however, to meet the required CO_2 storage targets, these large saline formations form the basis for Improved Pore Space Utilisation review.

Economies of scale dictate that the better the utilisation of a resource the more cost-efficient an operation (unless the cost of advanced utilisation outweighs the benefit). The capital cost of a pipeline, and development of a storage site, in most cases, would be further offset if the pore space utilisation is enhanced. The scale of the site to be appraised and monitored, including number of wells and impact to land owners, would be significantly reduced, if the pore space utilisation is enhanced.

The purpose of this task force study is to examine options to improve the utilisation of the pore space resource. This study considers modifying the manner of CO_2 injection to better utilise the resource. The key challenges for better utilisation of the resource addressed in this study are associated with overcoming the effect of buoyancy, improving the residual trapping process, and increasing the rate of transition from free-phase to dissolved phase.

This includes the examination of existing technologies developed in the hydrocarbon industry, maturing pressure management technology, and innovative emerging technologies, as well as general principles for storage operations.

1. Improved sweep efficiency techniques from the oil and gas sector
2. Pressure management
3. Microbubble injection
4. CO_2 saturated water injection combined with geothermal energy production
5. Compositional, temperature and pressure swing injection

This report **does not** go into details around well design (well orientation, number of wells, perforation, flow controls, well switching, etc), as these approaches are site specific and are reasonably well understood in the petroleum industry. However, the authors do recommend a future investigation of key learning from existing well design and well operation practices for improving reservoir utilisation.

The report also **does not** address any technical concepts regarding reservoir stimulation to increase utilisation. The authors see these as unnecessary techniques at the present level for the CCS industry, and present unnecessary risk in terms of long–term, safe CO_2 containment.

1.2 Storage Efficiency

The storage efficiency is a key parameter which describes the proportion of pore volume within the target storage complex reservoir volume that can be filled with CO_2 given the development options considered.

This ranges from 2 to 5% in some open aquifers without structures, through to 70-80% in highly depleted gas fields (see Figure 1 for an example from the UK). It is broadly the equivalent of recovery factor in the oil and gas industry.

The lifecycle unit cost of CO_2 transport and storage developments is complex and dependent upon many factors. The influence of some factors such as the length of the pipeline or the number and depth of wells required are both obvious and clear. Factors such as the volume of CO_2 stored in any project are equally important but often less obvious. Whilst storage efficiency is less well understood than other factors, it is a fundamental influence on overall lifecycle costs. Storage efficiency is high in pressure depleted gas fields which means that a large mass of CO_2 can be stored safely in a relatively small area. This means fewer platforms and wells and lower monitoring costs.

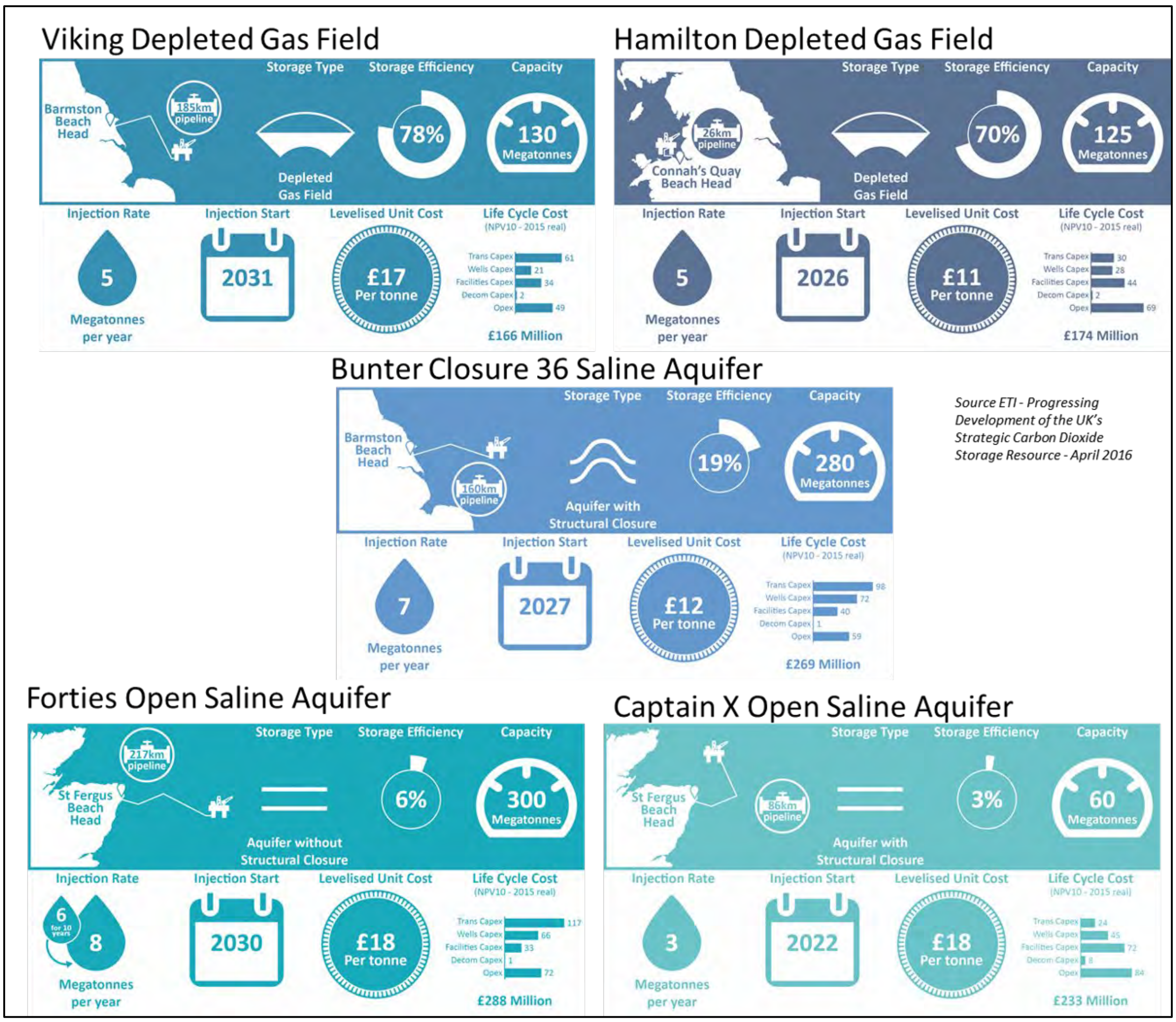

Figure 1: Source ETI - Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource - April 2016. A clear difference in storage efficiency is noted between the depleted gas fields (70 – 78%) to the saline aquifers (3 – 19%)

1.3 Dynamic Capacity

The dynamic capacity of the formation also plays an important role in how much of the pore space can be ultimately utilised. While there are cases where high storage efficiency can be achieved, a rapid build-up in pressure due, in some saline formations, to the injection of CO_2 results in much of the overall pore space resource not being accessed. An understanding of the dynamic capacity is therefore required to plan an appropriate injection rate and number of injection points to manage pressure build up whilst utilising the site effectively.

There are two methods for assessing CO_2 storage capacity:

1. Static (independent of time and including volumetric estimates using pressure build-up data)
2. Dynamic (where properties vary with time and include analytical approaches and numerical simulation) as defined by Pickup, 2013.

These methods are summarised in Table 1.

Table 1 Summary of static and dynamic capacity methods (after Pickup, 2013)

	Method	Summary
Static	Volumetric	Calculate formation pore volume Assume a storage efficiency Simple approach
	Pressure build-up	Assume a closed system Estimate the maximum allowable pressure build-up Calculate CO_2 volume from total compressibility and pressure increase
Dynamic	Semi-closed	Similar to pressure build-up method, but allows water to leak through the seals Does not assume zero permeability in seals Assumed CO_2 will not leak out because capillary entry pressure too high
	Pressure build-up at wells	Assumes pressure at injection well is the limiting factor Uses an analytical formula to estimate the injection pressure Assumes average pressure build-up throughout aquifer Assumes homogenous aquifer and sharp interface between CO_2 and brine
	Material Balance	Similar to the pressure build-up method, but update calculations with time
	Decline curve analysis	Monitor pressure build-up in a CO_2 injection site Opposite of decline curve analysis in a hydrocarbon reservoir Injection rate gradually declines as pressure builds up
	Reservoir simulation	Construct a detailed geological model Perform fluid flow simulations Requires most data and is the most time-consuming method

Dynamic CO_2 storage capacities are estimated using a 3D model that incorporates a structural framework with information such as porosity, permeability and geological formation character. Dynamic simulations using this model are then required to make the capacity estimate by utilising information about the effects of dynamic variables such as the number of wells, length of injection, rate of injection and the time to inject a given mass of CO_2 into a target storage volume. Temperature, pressure and total dissolved solids (TDS) data can also be used in the models to determine fluid properties such as CO_2 density, viscosity and dissolution coefficients (Gorecki *et al.* 2014). There is a risk that storage capacities could be overestimated if dynamic conditions are not applied and the properties of open and closed formations are not considered. These numerical simulations can be used to assess pressure build-up in order to help with the design of injection strategies (Babaei *et al.* 2016).

The size of the storage site and the type of boundary is of importance, for example in a small closed aquifer injected CO_2 will quickly reach the boundary and the CO_2 must be accommodated by compressibility of the formation and water (Bachu, 2015). In an actual storage site in this scenario the maximum pressure is likely to be reached around the injection wells or at the shallowest part of the structure and the pressure is limited by regulatory agencies to a percentage of the fracture pressure (Bachu, 2015).

1.4 Residual Trapping

There are several CO_2 trapping mechanisms which operate over different time scales: structural/stratigraphic and hydrodynamic trapping; residual trapping (capillary trapping); dissolution/solubility trapping; and mineral trapping (Bachu *et al.* 2007, Holloway *et al.* 2006).

Residual trapping, along with dissolution and mineral trapping, occurs over longer timescales than structural/stratigraphic and hydrodynamic trapping. These trapping mechanisms are an important aspect of storage security and safety when storing CO_2 in geological formations and primarily occur once injection into the storage formation has ceased (Bachu *et al.* 2007, Gorecki *et al.* 2014, Juanes *et al.* 2006). Recent studies suggest that up to 90% of the total storage capacity may be associated with residual trapping which will affect the extent of plume migration within the reservoir (Warwick, 2013; Nui *et al.* 2015). Research at the Frio Brine pilot study, USA, estimated that residual trapping for the conditions encountered there accounted for approximately 30% of the injected CO_2 (Horvorka *et al.* 2004).

Residual trapping has been extensively researched in the field of hydrocarbon exploration, mainly because it influences the ultimate oil recovery during production processes. When water is injected to enhance the recovery of hydrocarbons, there will ultimately be residually trapped oil remaining and this provides an analogue for residual trapping in CO_2 storage capacity (Nui *et al.* 2015).

As the injected CO_2 moves through the pore space of the formation it migrates upwards under buoyancy-driven flow and continues to do so after the cessation of injection. In most cases the pore space that CO_2 is injected into is naturally water-wet (wetting-phase) and the CO_2 being injected into the reservoir is a non-wetting phase (Juanes *et al*. 2006). When CO_2 enters the pores, some of the pore fluid remains in place (i.e. not all of it is displaced). As the plume continues to migrate through the formation, some of the pore space that the CO_2 occupied is refilled by the pore fluid. As the CO_2 is displaced at the trailing edge of the CO_2 plume, snap-off/disconnection of small amounts of CO_2 (part of a process known as imbibition) may occur (Juanes *et al.* 2006). These disconnected fractions of CO_2 are immobile and remain in pore spaces isolated from the main plume and is known commonly as residual trapping (Bachu *et al.* 2007; Juanes *et al.* 2006; Nui *et al.* 2015; Zuo and Benson, 2014).

Bachu *et al.* (2007) link residual trapping to hydrodynamic trapping because of its relationship with a migrating plume of CO_2. Their definition of residual trapping is '*the irreducible gas saturation left in the wake of a migrating stream or plume of CO_2 when water moves back into the pore space, after it was expelled from the pore space by the injected and/or migrating CO_2*'.

They present the following equation for storage capacity in residual-gas traps:

$$\mathbf{V_{CO2t} = \Delta V_{trap} \phi S_{CO2t}}$$

Where:

V_{CO2t} is the theoretical volume available for CO_2 storage

ΔV_{trap} is the rock volume previously saturated with CO_2 that is invaded by water

Φ is the formation porosity

S_{CO2t} is the trapped CO_2 saturation

It should be noted that, because residual trapping is time dependent, the amount trapped by this method can increase over time while the CO_2 plume continues to migrate (Bachu *et al.* 2007) and the trapped CO_2 saturation (**S_{CO2t}**) and the rock volume (**ΔV_{trap}**) can only be determined using numerical simulations (Juanes *et al.* (2006); Bachu *et al.* 2007).

Juanes at al. (2006) created simulations of injection and migration of CO_2 in a reservoir, one of the models assumed that all the injected CO_2 would migrate vertically as one plume with no residual CO_2 trapped. This model assumes a gas cap is formed under the cap rock creating the seal for the reservoir. A different scenario assumed there would be CO_2 residually trapped in pore spaces at the tail end of the migrating plume. This model predicted that after 500 years or less almost all the CO_2 is trapped within the geological formation and the CO_2 is spread over a larger area within the reservoir (differing from the first model which would have a concentrated plume of mobile CO_2). The second model is assumed to be more realistic and is likely to be more advantageous for storage of CO_2 by lowering the risk of leakage due to the presence of less mobile gas and increasing the chances of dissolution or mineral trapping (Juanes at al., 2006; Bentham & Kirk, 2005). Juanes at al. (2006) also conclude that high-resolution models are necessary to make an accurate assessment of the different storage/trapping mechanisms, if the model is too coarse it can result in an over-estimate of the sweep through the formation and the subsequent capillary (residual) trapping.

2 Non-Technical Issues Related to Improved Pore Space Utilisation

Current regulations concerned with CO_2 capture and storage (CCS) mean that the licensing of CO_2 storage sites is likely to be undertaken on a first-come, first-served (FCFS) basis. Applications for licenses of individual projects are submitted to regulators and the basis of the regulators' assessment will be primarily to consider if the site is fit for purpose as a storage site for CO_2 and is designed to protect the interests of pre-existing users. The following summary on storage resource optimisation is based on an IEAGHG report (2014), 'Comparing Different Approaches to Managing CO_2 Storage Resources in Mature CCS Futures'.

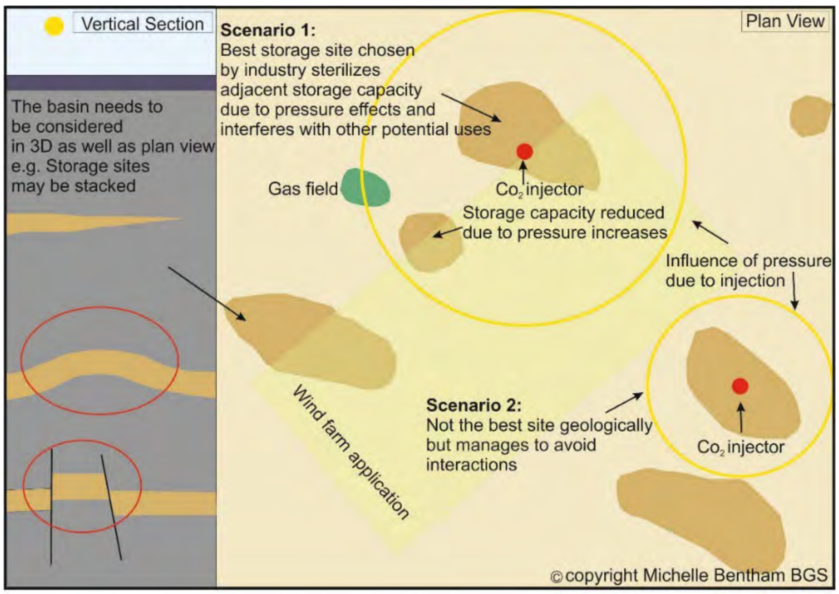

Figure 2: Conceptual view of spatial and subsurface interactions which might limit storage site selection, using a hypothetical example of gas fields and two storage site scenarios in the UK Southern North Sea

Storage sites for CO_2 will be selected by the operators on a 'most economically advantageous' basis, to meet the needs of individual clusters of CCS projects. Another IEAGHG study (2013), 'Interaction of CO_2 storage with subsurface resources', highlighted that sedimentary basins have multiple potential uses – hence there is potential for CO_2 storage projects to conflict with other subsurface and surface users (example shown in Figure 2). This report showed that increased pore fluid pressure in any reservoir formation (resulting from the injection of CO_2) may reduce storage capacity and increase costs in adjacent sites, which could potentially reduce the efficient use of the storage resource. Therefore, a more strategic approach would be required when dealing with sedimentary basins to ensure such formations realise their full resource potential. This raises important questions, including:

- How can CO_2 storage capacity be fully utilised in the presence of potentially competing uses of the subsurface and overlying ground surface or seabed?
- How should storage boundaries be defined in potentially pressure-interacting projects?

- How should potentially interacting resources e.g. CO_2 storage, hydrocarbon exploration and production and natural gas storage be developed most economically in the light of national or jurisdictional policies?

Factors which may influence the optimisation of a basin include the cost, risk minimisation, access to a range of uses of the basin including the ground surface and seabed, and the value of the resource. Such factors would need to be considered within the framework of government energy policies. It may also be necessary to look at other, perhaps less tangible potential future uses of the basin.

It is crucial for the operator and regulator to understand the consequences of a pressure increase over an area much larger than the extent of the CO_2 plume itself. It makes sense that an overview of the region (including future uses of the subsurface) is the responsibility of the relevant authority. The operator should be responsible for simulating the extent of the pressure footprint and the regulator for assessing the validity of this modelling. The main benefit of a FCFS approach is that the operator has the final decision on where to develop CO_2 storage, and the approach should work for multiple-stacked sites. Potential drawbacks of this approach include possible reduced storage capacities (in adjacent future storage sites), difficulties for monitoring and a lack of regional storage optimisation. In addition, the FCFS methodology may not lead to a pathway of overall least cost development for storage. To avoid or reduce potential negative interactions, some strategy management is likely to be necessary in most regions.

2.1 UK Regulations and Southern North Sea Case Study

The 2012 UK CCS Roadmap noted that the UK has extensive storage capacity in the North Sea and clusters of power stations/industrial plants which could share knowledge and infrastructure to develop CO_2 storage. At the time the storage roadmap set out specific activities that the UK government would focus on. This has been recently (November 2018) reset through the publication of the 'Clean Growth The UK Carbon Capture Usage and Storage deployment pathway An Action Plan' (UK Government, 2018) The UK Government has undertaken several significant activities for storage research and demonstration (R&D) including a commercialisation competition, the 2016 UK storage appraisal project (ETI, 2016) and a coordinated research, development and innovation programme.

UK-specific case studies described in the IEAGHG (2014) report illustrate the range of potential users/ conflicts which could be anticipated as more storage sites are developed. The main classes of potential CO_2 storage sites used are saline water-bearing domes in the Bunter Sandstone formation; gas fields in the Bunter Sandstone; gas fields in the Leman Sandstone; and gas fields in Jurassic limestones. Potential users or conflicts identified in IEAGHG's report include hydrocarbon operations, gas storage and other CCS sites (all subsurface users), and wind farms, dredging areas, pipelines, other operators, environmental protection areas and shipping routes (surface users). Scenarios were developed (FCFS and managed storage resource) to run from 2020 to 2050, to illustrate the interactions that may occur because of CO_2 injection.

The managed storage resource scenario demonstrates that CCS could face competition from other nearby CCS projects, offshore wind farms, gas storage sites and hydrocarbon production operations; however, it is likely that the development of both options could occur as demand for storage capacity increases, for reasons explained in the report. For example, offshore wind farms could present a physical barrier to accessing any potential storage sites in terms of laying down infrastructure and monitoring above a site, including the safety zones that may be imposed around turbines.

2.2 Underground Storage Permitting for CO_2 in the Netherlands

There are many R&D efforts underway in the Netherlands, and the national government works along an organisational model of a privately-run CCS market (where the initiative for action comes from the emitting operators themselves) and the government's role is one of a supervisor. It is interesting to note that the 'Inpassingsplan' (July 2008) under the Spatial Planning Act gives the Dutch government the right to adapt spatial planning by district/local governments in the circumstance of projects of national importance. The Dutch subsurface contains numerous gas fields and the policy of government is aimed at the use of depleted gas fields as CO_2 storage facilities.

There is the potential for competition within the surface and subsurface in the Netherlands. Using existing infrastructure is much more favourable than drilling new wells, but additional issues at the surface may arise, including land use conflicts, potential ground movements and induced seismicity. Public acceptance is likely the biggest barrier to CO_2 storage in the Netherlands and for this reason, at this stage it is only being considered offshore. In the subsurface, competition between users may arise in an onshore environment, where the storage of CO_2 may theoretically prevent gas fields from being used for other storage. Other potential competition in onshore areas may arise from nearby geothermal producers and injector pairs, or salt production activities from layers directly above the storage reservoir. A key potential offshore conflict is the issue of connectivity and pressure communication with adjacent fields under development or production.

2.3 Managing the Pore Space in Alberta, Canada

There are various activities and legislations to enable CCS and the storage of CO_2. The Alberta government assumes long-term liability (a significant uncertainty for CCS) for a storage site once a closure certificate has been issued, thus improving the ability for operators to plan/execute and ensuring the protection of the public. Steps have already been taken by the government to manage the positive and negative interactions between CCS and hydrocarbon resources. It is explicitly mandated in legislation that 'CCS projects will not interfere with or negatively impact oil and gas projects in the province'. The 'pore space tenure' process is the primary process to ensure that CCS development will not negatively impact the hydrocarbon industry in any way. Where there is high demand for pore space tenure in an area where pore space tenure has already been allocated, the provincial government must introduce policy and regulations to incentivise operators to allow access to their pore space for the storage of CO_2. There are currently no regulations for this, but portions of some Acts allow for the transfer of tenure and for Alberta, it is clear that 'market considerations should be a primary driver behind third party access to sequestration tenure and CO_2 injection'. The Albertan energy regulator has a well-developed process for evaluating and managing subsurface resource interaction, another process to encourage development in CCS.

2.4 Conclusions & Recommendations

There are various approaches to storage management, which are highly dependent on the jurisdiction involved. Most commonly, jurisdictions manage their pore space on a FCFS basis, in which operators will be able to identify their preferred CO_2 storage site. The operators' decision on a preferred site will be based on their specific geological, technical and financial criteria.

Management of storage on this FCFS basis is likely to be sustainable in the short to medium term especially in areas with abundant storage potential. However, there will be competition for the pore space in all regions; an issue likely to become more pronounced as CCS develops and matures, particularly in systems where pressure build is high. In some jurisdictions there is already a determined hierarchy of uses or constraints, but it must be noted that in some countries onshore storage is not considered due to public acceptance issues. Because of this, planning frameworks have already been developed to some extent in many countries considering the deployment of CCS. A strategic managed approach to a large formation or regional area may be desirable in certain scenarios of future CO_2 storage. The costs and benefits of such approaches have not yet been established, so studies that evaluate methods to optimise infrastructure for exploration will become increasingly important.

To understand the potential consequences of multiple storage scenarios occurring at the same time, a regional storage characterisation is recommended. Clusters of storage sites could be developed where regions have multiple or connected storage options. However, there is a current knowledge gap, and related policy approach, to determine the amount of pre-competitive characterisation needed to help develop policy for leasing. In addition to site characterisation, a detailed techno-economic evaluation of storage clusters would also be required. The UK case study detailed in Section 4 of the IEAGHG 2014 report demonstrates that targeting fewer, but larger, more geographically dispersed storage sites could meet future requirements as an alternative to clusters. Such large sites could provide enough storage capacity for multiple capture plants, and, in the USA, private pore space ownership may inhibit the development of clusters (if a lack of strategic policy occurs).

EOR sites have been identified as potential CCS resources but uncertainties arise for CO_2-EOR storage for various reasons. For ensuring net CO_2 emission reductions, an 'advanced CO_2-EOR' operation should be considered, where more CO_2 is stored permanently than the resulting operation and produced oil would emit. The economic viability of CO_2-EOR operations is a major issue as there are unknown cost-curves (cost of supplied CO_2 and future oil price fluctuations) and uncertainty with capital markets. Other uncertainties include the regulatory environments and public acceptance. EOR for the storage of CO_2 is an interesting and attainable strategy but would need much legal and regulatory management and policies that do not disincentivise existing commercial CO_2-EOR.

3 Improved Sweep Efficiency from the Oil and Gas Sector

Improving sweep efficiency in any injection project has been a popular topic during past decades. Much work has been done using water and CO_2 to enhance oil recovery, yet limited effort has been carried out to transfer these lessons to the CO_2 storage field. This study has undertaken a short literature review of some of the improved sweep efficiency technologies that have been considered for application in the geological storage of CO_2.

The main adding agents for improving sweep efficiencies in the oil and gas industry have been polymers, surfactants and foams and infill drilling.

1. Polymers: Commonly used as thickening agents to increase the viscosity of the formation fluid in the high permeable zones to redirect the injected fluid into the low permeable layers.
2. Surfactants: Used to change the interfacial tension between the injection and the formation fluid to reduce the residual saturation of the formation fluid.
3. Foams: Used to physically block the high permeable zones around the wellbore to redirect the injection fluid towards low permeable layers.
4. Infill drilling: Used to introduce new and different flow paths from injectors reaching parts of the reservoir that were previously unswept. Selective perforation within the injection interval and horizontal well geometries can also assist with this. As noted previously, this report does not go into details around wells and completion design.

Kim and Santamarina (2014), who undertook a study of engineered CO_2 injection, categorised four different methodologies to improve the sweep efficiency of CO_2 injection as follows:

1. Increased CO_2 viscosity and foams: Increasing viscosity can be achieved by using polymers (Alvarado and Manrique, 2010; Enick *et al*. 2010; Huh and Rossen, 2008). Whereas, foams enhance sweep efficiency by preferentially blocking the larger flow channels forcing CO_2 migration into smaller pores (Enick and Ammer, 1998; Farajzadeh *et al*. 2009).
2. Modifying the capillary factor: the most obvious strategy is to modify the CO_2–H_2O interfacial tension using surfactants (da Rocha *et al*. 1999; Dickson *et al*. 2005; Ryoo *et al*. 2003; Stone *et al.* 2004).
3. Sequential fluid injection: Viscous fingering is lessened, and CO_2 displacement is enhanced by the intermediate injection of a fluid with density, viscosity, and wetting properties that are between the properties of brine and CO_2 (Alvarado and Manrique, 2010).
4. Bio-clogging: Preferential bio-clogging of the larger water-filled pores will cause flow to divert to low-permeability channels. Compiled results suggest that bio-clogging will be most effective most sediments (Rebata-Landa & Santamarina, 2012).

The effectiveness of foam injection for improving the efficiency of CO_2 displacement in CO_2 EOR has been performed in lab-based experiments on core (Casteel and Djabbarah, 1998). The core-flow experiments involved the simultaneous injection of CO_2 into two water flooded cores (Berea Sandstone). The cores were arranged in parallel and had different permeabilities. The test temperature and pressure were constant and above the critical conditions for CO_2. Three types of core-flow tests, involving injection of CO_2 to displace oil, injection of alternate slugs of CO_2 and brine, and injection of foaming agents, were conducted. The foaming agents were injected before CO_2 injection and after CO_2 had displaced oil from the more permeable core. The results show that in-situ foam generation is an effective method for improving CO_2 displacement efficiency. Foam was most effective when the foaming agent was injected after CO_2 displaced the oil from the more permeable core. The improved sweep efficiency was caused by the tendency of the foam to be generated preferentially in the more permeable core. The foam increased resistance to flow in this core and caused more CO_2 to flow through the less permeable core. Although the experiments were performed to assist EOR related projects, it can also be applied for CO_2 storage projects and the same experimental approach can be deployed to understand the impact of foam injection on CO_2 injection efficiency in CCS projects.

University of Texas Austin and Rice University developed innovative CO_2 foam concepts and injection schemes, based on core flooding experiments, for improving CO_2 sweep efficiency for both sandstone and carbonate formations (Nguyen *et al*. 2015). One of the important findings was that at very low fluid rates (i.e. far field rate conditions), the mobility of CO_2 in foam is quite uniform in both high and low permeability rocks. This indicates that in higher permeability zones foam is better for restricting the preferential flow of CO_2, resulting in higher sweep efficiency. For high flow rates (i.e. near wellbore rate conditions), the effective permeability of CO_2 increases with injection rates. Therefore, strong foam that reduces injectivity does not develop near the wellbore region. The core flood results are also useful for understanding local foam rheological behaviours and empirical approach-based foam modelling.

Hughes (2010) performed a study to evaluate the enhancement of CO_2 flooding. The project focused on relating laboratory, theoretical and simulation studies to actual field performance in a CO_2 flood to understand and mitigate problems of areal and vertical sweep efficiency. The work found that an understanding of vertical and areal heterogeneity is crucial for understanding sweep processes as well as understanding appropriate mitigation techniques to improve the sweep. Production and injection logs can provide some understanding of that heterogeneity when core data is not available. The cased-hole saturation logs developed in the project were also an important part of the evaluation of vertical heterogeneity. Evaluation of injection well/production (or monitoring) well connectivity through statistical or numerical techniques were found to be successful in evaluating CO_2 floods. Detailed simulation studies of pattern areas proved insightful both for doing a "post-mortem" analysis of the pilot area as well as a late-term, active portion of the Little Creek Field. This work also evaluated options for improving sweep in the current flood. The simulation study was successful due to the integration of a large amount of data supplied by the operator as well as collected through the course of the project. While most projects would not have the abundance of data, integration of the available data continues to be critical for both the design and evaluation stages of CO_2 floods.

Shamshiri and Jafarpour (2010) developed a new framework to optimise flooding sweep efficiency in geologic formations with heterogenous properties and demonstrate its application to waterflooding and geological CO_2 sequestration problems. The results from applying the proposed approach to optimization of geologic CO_2 storage problems illustrate the effectiveness of the algorithm in improving residual and solubility trapping by increasing the contact between available fresh brine and the injected CO_2 plume through a more uniform distribution of CO_2 in the aquifer.

Good vertical injection conformance is required for good sweep efficiency. If the CO_2 is not able to sweep all the layers, the overall storage capacity will diminish. Goyal et. al. (2017) introduced new high expansion ratio inflatable plugs to be applied in a polymer injection field. This is a mechanical solution that helped the operator to selectively produce from the poorly swept zones. A similar solution can be deployed in the case of CO_2 injection by isolating the zones which have been overly flooded and expose the injection stream to isolated zones.

Enick and Olson (2012) performed a literature review of the history and development of CO_2 mobility control and profile modification technologies in the hope that stimulating renewed interest in these chemical techniques will help to catalyse new efforts to overcome the geologic and process limitations such as poor sweep efficiency, unfavourable injectivity profiles, gravity override, early breakthrough, and viscous fingering. CO_2 mobility control technologies are in-depth, long-term processes that cause CO_2 to exhibit mobility comparable to oil. Profile modification and conformance control are achieved by a near-wellbore, short-term process primarily intended to greatly reduce the permeability of a thief zone.

The results of 40 years of research and field tests clearly indicate that mobility and conformance control for CO_2 EOR with thickeners, foams, and gels can be technically and economically attainable for some fields. Although the compiled literature review CO_2 EOR related, the suggested techniques can also be used in the geological CO_2 storage. The following technologies were recommended as results of their work:

1. CO_2 Viscosifiers (Direct Thickeners)
2. Near-Wellbore Conformance Control with CO_2 Foams and Gels
3. In-Depth Mobility Control CO_2 Foams

Another issue that sometimes reduces the efficiency of using the pore space is the existence of high permeability features, such as fissures, fractures and eroded-out zones. Placing crosslink conformance polymer gels or other types of blocking agents in injection wells might generate the required diversion agent. Crespo et. al. (2014) evaluated a high molecular weight organically crosslinked polymer gel system for such scenarios. Similarly, this has been tested for EOR projects and yet to be examined in CO_2 storage reservoirs where we only have two phases of CO_2 and brine.

Although the previous literature has primarily been IOR/EOR related, most of the techniques can be applicable for geological CO_2 storage in saline aquifers as well after being tested in laboratory scale or field trial projects.

4 Pressure Management

The displacement of native pore fluids during CO_2 injection operations causes an increase in the pore pressure in the region surrounding the wellbore. In sites where geological integrity is insufficiently understood, excessive pressure increases could initiate failure of the caprock and reactivation of existing faults, putting secure containment of CO_2 at risk. Removal of brine from a CO_2 storage reservoir, as a pressure management technology, has been investigated for several years as a mechanism to reduce the risk caused by pore pressure increases.

Pressure management can also play a role in optimising the storage efficiency of a CO_2 storage site. As mentioned in 1.3, the effect of dynamic capacity can be a limiting factor for CO_2 storage.

4.1 Background

This approach can be through the appropriate placement and operation of pressure relief wells to hinder the lateral spread of a plume in the up-dip direction, or less commonly considered by increased injection pressures to enable CO_2 flow into lower permeability paths.

In an appropriately characterised storage site, pressure thresholds, and associated uncertainties are well understood prior to an injection operation. Safe operations are designed so that pressure change is restricted below these thresholds to minimise the risk to geological integrity, meaning injectivity and storage capacity may need to be reduced.

The magnitude and lateral extent of this pressure increase is determined by several parameters including (but not limited to) porosity, permeability, thickness and extent of the reservoir, CO_2 injection rate, the number and placement of injection wells, any barriers to fluid flow, and any fluids extracted from the reservoir. Understanding the pore pressure distribution is essential to ensure optimal storage efficiency. Designing a safe and reliable monitoring concept with a clear purpose of discriminating pressure and saturation changes is crucial for maintenance of mechanical stability. Ensuring the long-term safety and conformance of the storage complex forms a fundamental prerequisite for an operators' CCS investment decision. Early detection of deviations from the expected response is desirable; a focus on monitoring pore pressure changes is likely to be more cost-effective than alternative monitoring surveys.

To maximise the storage efficiency, CO_2 must be optimally distributed within the reservoir. Local pressure build-up, or drop-off, offers an early warning of sub-optimal CO_2 flow and may indicate an elevated risk of leakage and/or fracturing, due to reservoir heterogeneities or near well issues. For example, the In-Salah CO_2 storage project in Algeria experienced reactivation of a fracture network partway through the lower section of a 950m thick seal because of injection pressure, and pre-existing fractures (White *et al*. 2013). Another example, the Snøhvit CO_2 injection into the Tubåen Formation, experienced rapid pressure increase, caused by salt precipitated in the near wellbore formation and a reduced the injectivity (Hansen *et al*. 2013).

The CCS industry highlights the requirement for intelligent reservoir management methods with emphasis on pore pressure control to enhance overall storage capacity (Nazarian *et al.* 2013). The importance of fluid pressure management in CO_2 storage has been emphasised in several publications, either through numerical simulations (e.g. Zhou and Birkholzer, 2011; Buscheck *et al.* 2012) or practical experiences (e.g. Eiken *et al.* 2011; Hansen *et al.* 2013).

4.2 Modelling

Numerical flow simulations have previously been used to investigate the impact of heterogeneity, and flow barriers such as faults and dykes, on a CO_2 storage operation. For example, the EU FP7 ULTimateCO_2 project studied the long-term behaviour of pressure in a storage reservoir using a regional geological model of the Bunter Sandstone (UK Southern North Sea). Additionally, the EPSRC-funded CO_2 Injection and Storage project investigated the impact of coupled brine production and CO_2 injection using numerical simulations of a homogeneous box model. Furthermore, studies such as Mbia *et al.* (2014) have modelled the pressure propagation due to CO_2 injection on specific case studies to investigate how overpressure is built up and dissipated. These studies have demonstrated how saturation and pressure can be controlled with water extraction in reasonably homogenous reservoirs. Additionally, studies on pre-injection brine production by Buscheck *et al.* (2016) have shown that the resulting pressure drawdown can provide direct information about possible overpressure effects during CO_2 storage and may provide operators with pre-injection information to optimise storage efficiency. Analytical and semi-analytical models of pressure build-up during CO_2 injection are available (Mathias *et al.* 2011; Mathias *et al.* 2009a, b; Szulczewski *et al.* 2014). These predict the magnitude and extent of overpressure due to CO_2 injection for little computational cost

Strategies involving the extraction of water from CO_2 reservoirs could be the primary method of interventional pressure management for CO_2 storage reservoirs. Extraction of water from CO_2 storage reservoirs acts to decrease the pressure and increase the available pore space. This results in a larger capacity and greater utilisation of the pore space for CO_2 storage (Bergmo *et al.* 2014). Simulation show that water production is becoming increasingly important as a pressure management tool for CO_2 storage, and the Gorgon CO_2 Injection Project will utilise four water production wells to manage pressure build up. Modelling studies have investigated numerous aspects of water production: limiting local pressure increase near CO_2 injection sites (Bergmo *et al.* 2011; Buscheck *et al.* 2012); reducing the pressure spatial footprint (Buscheck *et al.* 2011; Court *et al.* 2012); providing an intervention when site pressure exceeds design limits (Le Guenan and Rohmer, 2011); and targeting a specific area which might be especially vulnerable to increased pressure (Birkholzer *et al.* 2012). Pressure reduction is most effective in reservoirs with high permeability, weak heterogeneity and with water production close to the CO_2 injection. Storage sites within large open aquifers tend to require less interventional pressure management than more compartmentalised reservoirs since the connected pore volume acts as a buffer, absorbing pressure increases from CO_2 injection (Chadwick *et al.* 2009). Yet, whilst the primary effect of injection is often observed close to the wellbore, Cihan *et al.* (2013) observed that the potential large-scale displacement of saline formation water may affect a spatial domain that is orders of magnitude greater than the footprint of the fluid substitution.

Pressure Relief

There are two distinct categories of pressure relief through water production: active and passive.

Active water production involves the pumping of water from the reservoir through wells at a specified rate. This allows the rate of water production to be controlled from the surface independent of the reservoir pressure. Active water production may even commence before CO_2 injection (Buscheck *et al.* 2014) and it has been proposed that it can a be used to drive CO_2 into the reservoir (passive injection) avoiding the need of overpressure at the injection points (Dempsey *et al.* 2014).

Passive water production is a deliberate pressure management intervention which allows water to be extracted from the reservoir, driven by pressure increases above hydrostatic values (Bergmo *et al.* 2011). There are significant similarities with naturally occurring leakage through pathways such as open wellbores, fractures and faults (Birkholzer *et al.* 2011). One of the benefits of passive water production is that no pumping equipment or power is required on site. There is also no risk of a net depletion effect on the aquifer because the water production is driven by pressure increase. Both active and passive water production may release the produced water either into suitable shallower aquifers or at the surface.

Increased Injection Pressure

Increasing, in a controlled manner, injection pressure is also a pressure management technique to improve pore space utilisation through improved CO_2 sweep. To do this, it is important to understand how reservoir heterogeneity influences trapping. Low permeability zones in heterogeneous reservoir, even at small-scale, can have significant effects on large-scale pore space utilisation. Where injection can safely occur at higher pressures, CO_2 can be introduced into these zones. Exactly how small-scale heterogeneities affect the CO_2 injection and trapping processes is still being developed and a better understanding fluid processes and reservoir influence, from the field scale to the pore scale is required. Work already underway by the GeoCquest gives us confidence that this will be possible (Benson *et al*. 2018).

4.3 Real World Example

The use of water production adds to the costs of any CO_2 storage operation primarily through the operational costs of additional production wells, water pumping and water disposal (Breunig *et al.* 2013; Neal *et al.* 2011). In addition, particularly for onshore sites with brine production, questions occur regarding the disposal of the produced water either in overlying aquifers or at the surface (Bourcier *et al.* 2011). The Gorgon project, based on Barrow Island - 100 km off Western Australia, involves possibility of brine extraction through four water production sites (Flett *et al.* 2008; Liu *et al.* 2015) to control pressure. Injection planned to start in 2014 with injection of 3.4 Mt/year, and pressure management using brine production wells in a linear configuration some 4–5 km from the injection wells (Birkholzer *et al.* 2012).

In order to demonstrate safe storage of CO_2, operators must perform both direct pressure monitoring at injection and monitoring wells, and indirect monitoring and modelling of the CO_2 plume. Direct information from pressure monitoring is an indispensable prerequisite to calibrate reservoir models, from which the spatial extent of the plume can be predicted. Indirect monitoring methods targeted at tracking CO_2 plume movement and advancement of the pressure front (Strickland *et al.* 2014) include mostly seismic and non-seismic geophysical methods (e.g., electrical/EM, gravity, or wellbore logging) as CO_2 detection tools. At the Snøhvit CO_2 storage operation in the Barents Sea, offshore Norway, an overpressure phenomenon was observed during the initial phase of injection. White *et al.* (2015) and Grude *et al.* (2013; 2014) utilised 4D seismic data to differentiate between pressure and saturation changes generated during CO_2 injection. Eventually, the injection perforations in the wellbore were relocated to an overlying storage formation where CO_2 storage ran smoothly (Hermanrud *et al.* 2013).

Long-running projects, such as the Ketzin pilot and Sleipner show that as more data become available, the match between modelled behaviour and observations improves (Chadwick and Noy, 2015; Kempka and Kühn, 2013). Although these examples provide confidence that demonstration of conformance is achievable in a wide range of settings, more projects are required to gain confidence that a conformance workflow can routinely achieve a sufficient match between observations and models.

5 Microbubble CO_2 Injection

Microbubbles have various unique features, such as small size, low buoyancy and high solubility, in comparison with normal-size bubbles, and have been applied to diversified areas such as medical imaging, device cleaning, food processing and aquafarming. In the area of CCS, there have been several proposals of microbubble CO_2 injection to increase the CO_2 storage resource by increasing storage efficiency or by diversifying feasible reservoir types. Microbubble CO_2 injected together with water is thought to enter smaller pore space and mostly shrink and dissolve rapidly into formation water (Koide & Xue, 2009). In combination with the lower buoyancy of microbubbles, this approach can optimise the CO_2 storage in open structure reservoirs, fractured rocks and tight reservoirs. This would make source-sink matching and CO_2 storage for small-scale emission sources easier. In a case where microbubble CO_2 is dissolved into ground water extracted from an aquifer and then returned into the aquifer, the CO_2 reservoir could be located shallower than 800 m (Suzuki *et al*. 2013) Targeted CO_2 reservoirs are usually 800m or deeper to inject CO_2 in the supercritical state. Microbubble CO_2 could be also injected directly into an aquifer through a porous filter placed on borehole casing or gas tubing (Xue *et al*. 2014). The direct microbubble CO_2 injection could be also be applied to EOR to improve sweep efficiency.

5.1 Characteristics and Generation Methods

A microbubble is defined as a bubble with a diameter in a range from 1 μm to 100 μm (ISO/TC281). Microbubbles have higher solubility than normal-size bubbles in water. Microbubbles therefore rise slowly, shrink and ultimately disappear, whereas a normal bubble rises rapidly and bursts at the water surface. The characteristic is attributed to its larger interfacial area per volume, low buoyancy, and a higher inner pressure.

Microbubbles can be generated in several ways, including,

(1) Pressurised dissolution: Gas is dissolved into liquid under high pressure and then depressurised to generate supersaturation conditions, where the dissolved gas turns into microbubbles;
(2) Shear stress breakup: Microbubbles are generated through the separation from the gas stream in liquid by generating shear stresses conditions (e.g. mechanical vibration);
(3) Cavitation: Ultrasound waves are used to induce cavitation in gas-dissolved liquid, which generates microbubbles due to rapid reduction of pressure;
(4) Micropore: A microporous media is used to generate microbubbles in rapid flow or under high pressure.

5.2 Microbubbles CO_2 for CCS

To generate CO_2 microbubbles for geological CO_2 storage or CO_2-EOR, the required methods needs to maintain pressure, as well as being able to operate in subsurface conditions which can be high temperature and high salinity. In addition, a system that generates microbubbles needs to be easily installed, have high reliability, easily maintained and have an overall low operational cost. Research to date has targeted a micropore filter for microbubble CO_2 generation at the borehole casing or pressurised dissolution, and conducted lab tests with core samples to compare characteristics and behaviour of CO_2 microbubbles generated with the filter and those of larger CO_2 bubbles from the viewpoint of geological CO_2 storage and CO_2-EOR (Xue *et al*. 2014; Akai *et al*. 2015; Xue, 2016).

The micropore filter (shown in Figure 3a) demonstrated a capability of generating microbubble CO_2 in the gaseous (6 MPa and 40°C), liquid (10 MPa and 20°C) and supercritical (10 MPa and 40°C) phases. A quantitative analysis with serial images of supercritical CO_2 microbubbles (~50 to ~200 μm) and a larger supercritical CO_2 bubble (~400 μm) released in pure water concluded that the solubility of microbubbles is 20% higher than that of the larger bubble (Figure 3b).

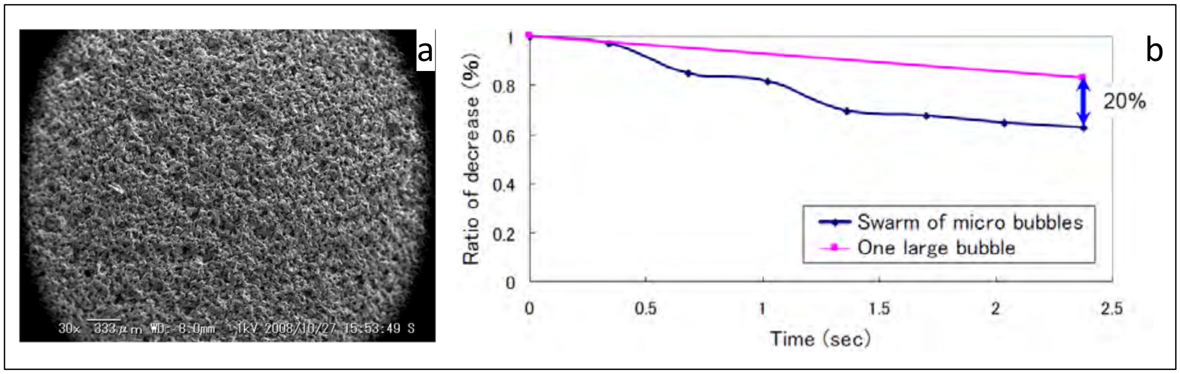

Figure 3: A scanning electron microscopic (SEM) image of a porous plate; b) CO_2 bubble dissolution

A series of two-phase lab tests with brine and CO_2 were conducted to simulate supercritical CO_2 injection for geological storage. In the tests, microbubble CO_2 and normal-size bubble CO_2 were injected at a rate of 0.05 ml/min into different brine-saturated Berea sandstone samples (70 mm long and 35 mm in diameter with the porosity of 18%) under conditions of a CO_2 reservoir (10.5 MPa and 40°C). The results show that microbubble CO_2 migrates more slowly, takes more time for breakthrough and shares more pore space than normal-size bubbles (Figure 4a). In Figure 4b, higher dissolution of microbubble CO_2 can be also observed at an early stage of injection. These results indicate that microbubble CO_2 injection has the potential of improving pore space utilisation.

The potential of microbubble CO_2 injection for higher pore space utilisation implies its potential of high sweep efficiency in a CO_2-EOR operation as well. To confirm the potential benefit, lab tests were conducted to simulate CO_2 injection for EOR with two 70 mm-long and 35 mm-diameter Berea sandstone core samples which have a similar porosity (18.5% and 17.5%). The cores were saturated initially with brine and then with oil (decane). Like the results of the two-phase tests previously shown, microbubble CO_2 migrated more slowly and sweeps more effectively than normal-size bubbles (Figure 5a). The microbubble CO_2 injection has 3% higher oil recovery rate (Figure 5b). The same test procedure was applied to core samples taken at a Japanese oilfield. In this case, microbubble injection presents clear advantage in oil recovery with > 10% higher rate than that for normal-size bubbles (Figure 6). The results imply that microbubble CO_2 injection has higher sweep efficiency in CO_2-EOR operation.

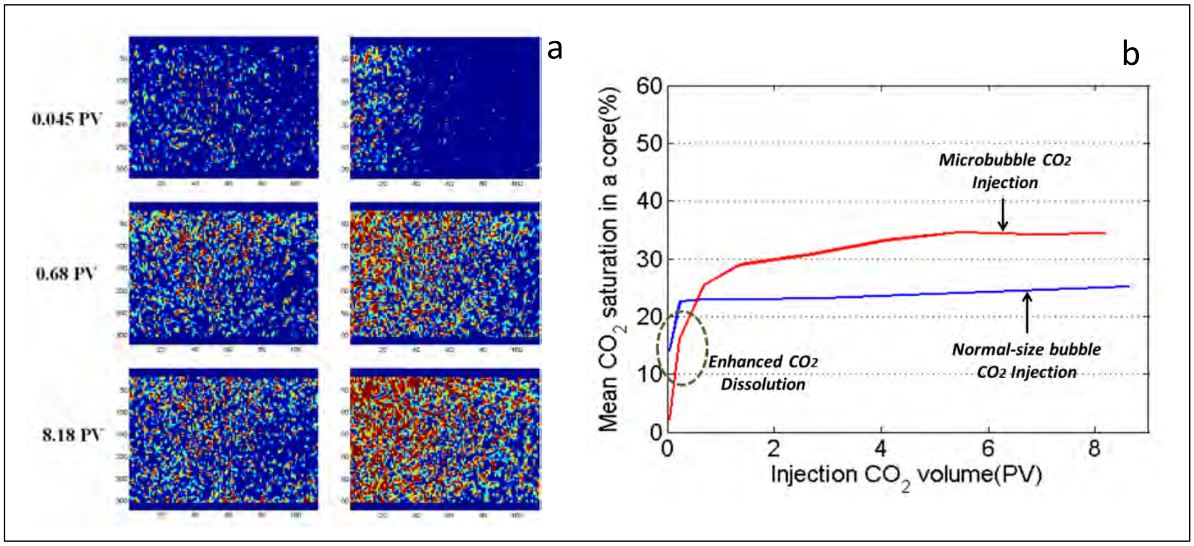

Figure 4: a) X-ray CT images of Brine-Saturated Cores with CO_2 Injection (Right: Microbubble CO2 Injection; Left: Normal-size Bubble CO2 Injection); b) CO_2 Saturation in Cores (PV - pore space volume and 0.045PV means injection of CO_2 equivalent to 4.5% of PV)

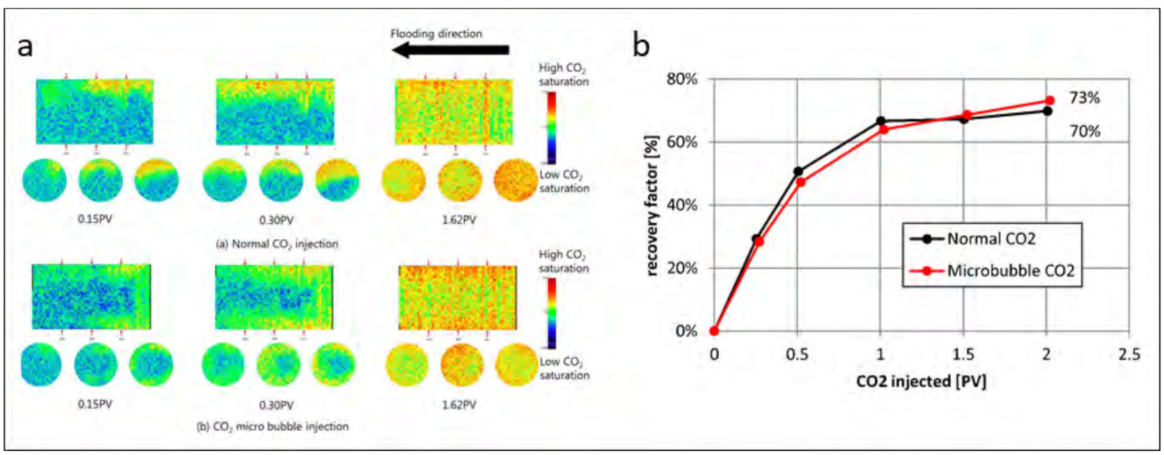

Figure 5: a) X-ray CT images of Brine/Oil- Saturated Cores with CO_2 Injection; b) Oil Recovery – Berea Cores

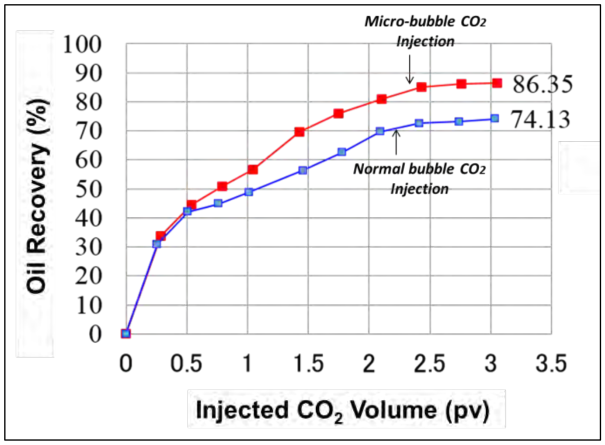

Figure 6: Oil Recovery – Cores Taken at an Oilfield.

Although further lab tests together with computational simulations are still required to make microbubble CO_2 injection technically available, field trials were initiated in Japan in 2018. A couple of prototype downhole tools for microbubble CO_2 injection equipped with the micropore filter were developed and tested in a 200m-deep well. With the most effective tool, microbubble CO_2 injection tests in a 900m-deep well are under planning to be initiated in 2019.

6 CO_2 Saturated Water Injection and Geothermal Energy Production

This chapter is a synthesis of literature by Blount *et al*. (2017), Blount *et al*. (2014), Galiègue & Laude (2017), Kervévan *et al*. (2016), Kervévan *et al*. (2013), Royer-Adnot & Le Gallo (2017). Complete references for this literature are found in 9 - References.

The CO_2 -DISSOLVED concept proposes an approach for targeting small-scale CO_2 emitters, combining CCS and the production of geothermal energy. This design combines capture, injection, and storage of dissolved CO_2 (rather than supercritical) in a deep saline aquifer with geothermal heat recovery. The CO_2 -DISSOLVED concept consists in coupling a patented CO_2 -brine dissolution technology to a geothermal loop with a hot brine production well for heat extraction and an injection well for re-injecting the cooled brine saturated with CO_2. This capture strategy makes it mandatory to use a water/brine movement provided by the geothermal facility.

The key feature of this innovative clean energy-CCS concept is the use of dissolved CO_2. The advantages of using a coupled system with no gas phase being present implies no pressure build-up effects, no displacement of the brine initially in place beyond the project footprint, and low leakage risk for the injected CO_2 to the surface**.** However, a physical limitation is the solubility of CO_2 in brine, which limits the rate and quantity of CO_2 injection in the aquifer. Consequently, the CO_2 -DISSOLVED concept is best suited for small-medium industrial CO_2 emitters and, as such, is complementary to the classical supercritical CCS more suited to high-rate emitters.

6.1 Technical Feasibility

This concept's main innovation comes from the capture technology that is selected (Blount *et al*. 2014). This technology is brought to the project by Partnering in Innovation, Inc. (a US company). The Pi-CO_2 capture method uses water as a physical solvent, circulating the water and emission gas through a cascade mass transfer system (MTS) located in a sealed deep large diameter well under ca. 25-60 bar hydrostatic pressure (Figure 7). The hydrostatic pressure significantly increases the solubility of gases in water. The system is closed loop with the high pressure non-dissolved separated gas fraction diverted to the surface and combined with heat to recover compression energy.

The flue gas is injected in the MTS at depth in the deep-water column. The gases (CO_2 and lesser competing gases) are concentrated through a cascading series of absorbers in the MTS. Water returning to the surface from the MTS becomes less pressured allowing for gas ex-solution, and this ex-solution drives the water circulation (gas lift pumping) so that additional energy and mechanical pumping are not needed for circulation. The non-CO_2 ex-solved gases are sequentially removed in the return line to produce near-pure CO_2. The system integrates compression and energy recovery processes at the surface to reduce parasitic load with heat exchange and turbo-machinery. Uniquely, the Pi-CO_2 process also removes SOx, NOx, vaporised metals, while capturing CO_2, in a single integrated process. The oxides are removed in compression condensate and at inter-cooler and after-cooler steps during flue gas compression (Blount *et al*. 2017). This in-process feature avoids expensive pre-treatment of the flue gas. Another interesting feature of the Pi-CO2 system is its expected easiness of construction since all the surface turbomachinery, heat exchange, and shaft installation equipment is currently available "off shelf". Moreover, as much of the installation is underground, the surface footprint is small.

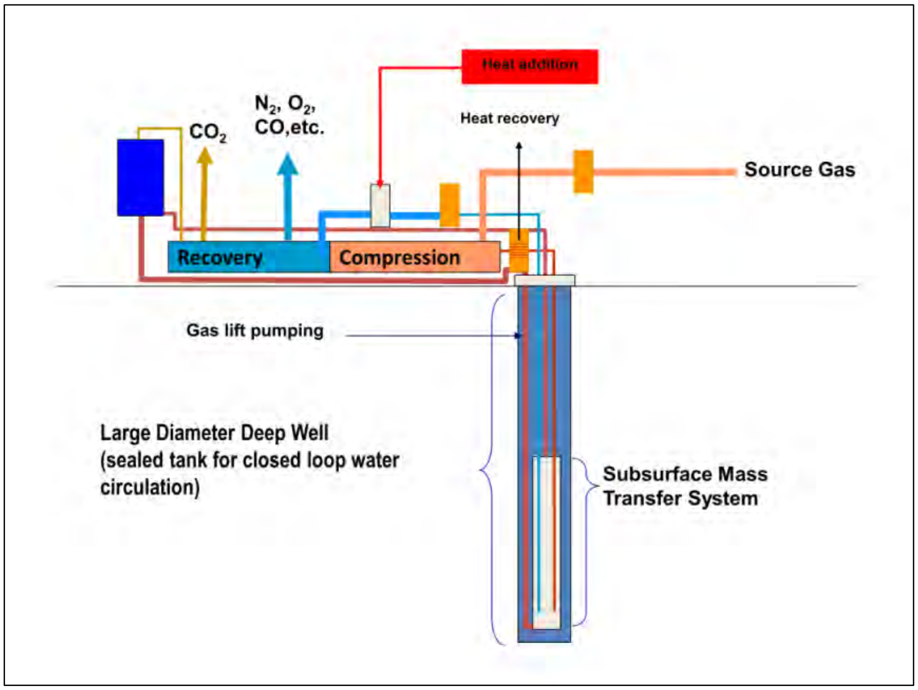

Figure 7: Simplified view of the Pi-CO_2 water-based in-well capture technology planned to be used in a CO_2 -DISSOLVED system.

The option of using a separated large-diameter well housing the Pi-CO_2 system and dedicated to the CO_2 capture operations was then considered (Figure 8). With this solution, this third well would be designed according to the actual needs in terms of CO_2 separation and injection, depending on the targeted flow-rate and on the flue gas composition. Once recovered at the surface, the separated CO_2 gas phase would then be injected in the doublet at a controlled mass-rate through a dedicated small-diameter pipe. This pipe would be ended at depth by a bubbler, specifically dimensioned to ensure complete CO_2 dissolution in brine before it reaches the storage aquifer. Mass transfer modelling proved the adequacy of such a system for easily dissolving several tens of kilotonnes of CO_2 per year. CFG Services (a BRGM subsidiary) confirmed that this system could be easily fitted in a standard geothermal injection well after a slight modification of the well head (equivalent to what is done for integrating an inhibitor injection line). An equivalent injection system for injection and dissolution at depth of CO_2 was successfully tested on the CarbFix site in Iceland.

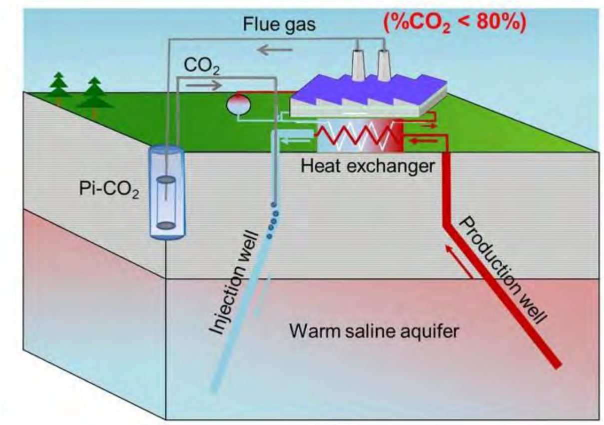

Figure 8: Design of a CO_2 -DISSOLVED facility: standard version including the geothermal doublet and a third large-diameter well housing the Pi-CO_2 mass transfer system, when the CO_2 rate in the flue gas is lower than 80%.

6.2 Applicability of the Concept

The technology applicability has been mapped at a country scale to potentially compatible sites. This was done by identifying and prioritising small rate industrial emitters (< 150,000 t per year of CO_2) that could potentially benefit from the application of this technology, to regions where reasonable geothermal resources occur. Three examples are presented hereafter: France, Germany, and the USA.

In France, the areas where the geothermal resources could potentially match the compatible industrial CO_2 emitters are composed by all the major sedimentary basins, i.e. the Paris Basin, the Aquitaine Basin, the Upper Rhine Graben, the Limagne and Bresse regions, and the Rhone corridor (blue and dark blue areas in Fig. 2). Then, 653 small to medium French emitters can be considered as potentially compatible with the CO_2-DISSOLVED concept (Figure 9). These 653 CO_2 sources have emitted a total amount of 25.1 Mt of CO_2 in 2011 (16.9% of the total French CO_2 emissions).

In Germany, the hydrothermal potential areas (proven or assumed) were considered for determining the potential areas of geothermal energy use. 242 small to medium emitters were located in favourable areas both for hydrothermal energy use and CO_2 storage. In total, these 242 CO_2 sources emitted 9.98 Mt of CO_2 in 2012 (7.1% of the total CO_2 emissions).

In the USA, the potential areas where the CO_2 storage could be coupled with geothermal activity are mostly concentrated in the western part of the USA, including Alaska and Hawaii. A few states along the east coast, including New York, Pennsylvania and West Virginia have low-temperature geothermal systems. Detailed information on the number of sources and emission totals for the small to medium emitters in the USA was not determined.

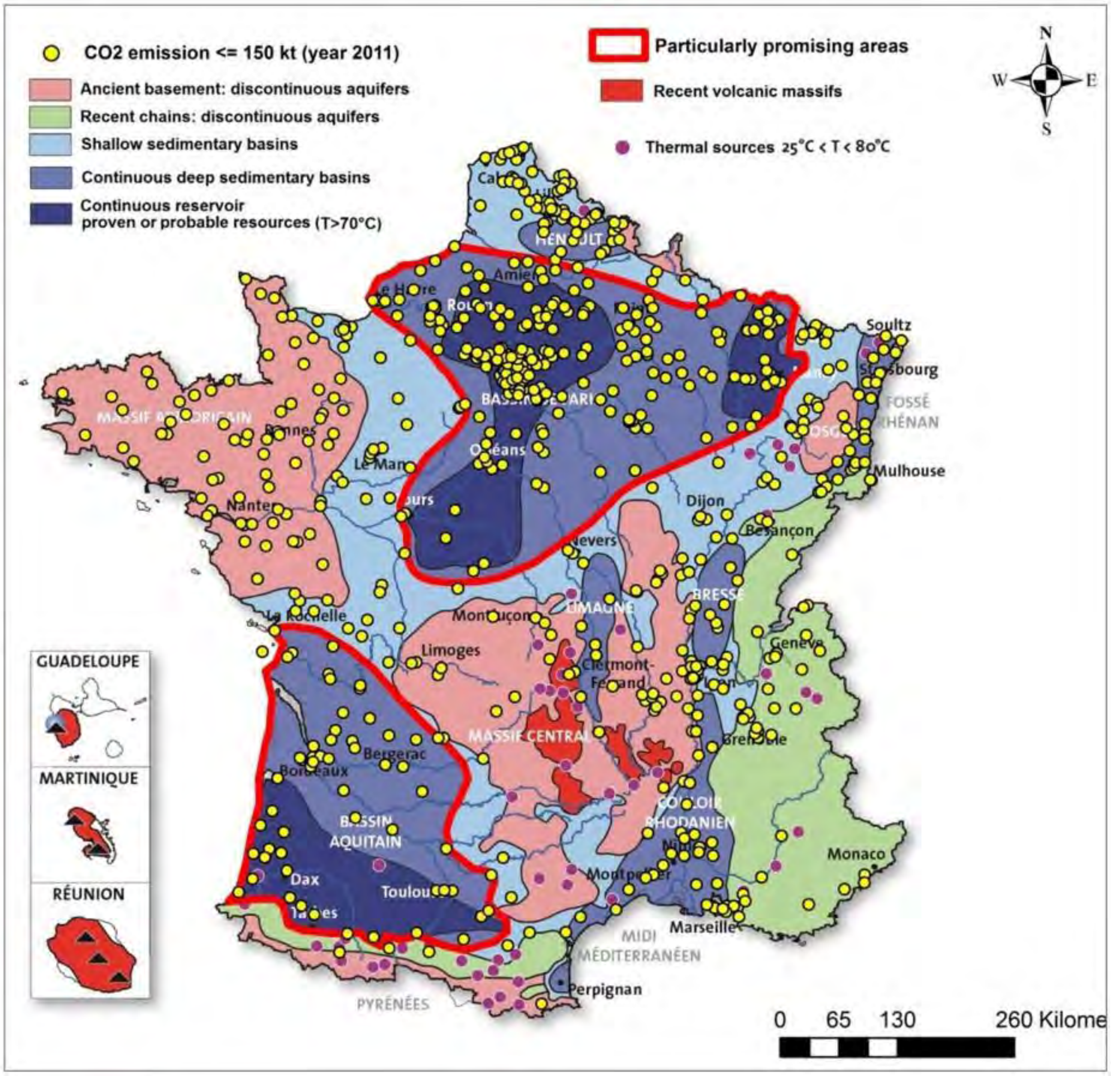

Figure 9: Example of mapping small to medium CO_2 emitters (ca. 10-150 kt/yr, yellow spots) to geothermal resources.

6.3 Economic Feasibility Study

To evaluate the CO_2-DISSOLVED concept, a preliminary economic analysis is performed based upon results from Laude *et al*. (2011) on a sugar beet refinery. The BECCS (Bio-Energy with CCS) approach (Fabbri *et al*. 2011) provides excellent environmental results with negative emissions due to the production of the bioethanol. However, on the economic standpoint, the performance of the project was poor due to the small volume of stored emissions that could not offset the required capital cost. Using the same base case plant, this paper presents the carbon and energy footprints and the economics of the CO_2-DISSOLVED concept. The work presented in this paper involves no specific process design and must therefore be considered as a conceptual study encompassing a significant level of uncertainty. Only the main equipment was considered based upon previous results which leads to uncertainties of more than 50%.

Based on a real case study, e.g. a sugar beet refinery, the CO_2 -DISSOLVED concept may reduce emission by 25% to 60% and energy consumption by 5 % to 30 % depending on the scenario.

Compared to the CCS case, the CO_2 -DISSOLVED concept showed an emission reduction from 15% to 50% while the corresponding non-renewable energy consumption was reduced by 5% to 30%. The CO_2 emission reduction is more important than the non-renewable energy consumption reduction due to compression energy requirements (even if compression power is reduced in the CO_2 -DISSOLVED case, the first stages of compression are consuming more energy).

However, the CAPEX requirement is reduced by 38 % to 47 % depending on the scenario considered. The cost per tonne of CO_2 avoided (stored + not emitted by the combustion due the use of geothermal energy) ranges from 39 to 72 $€_{2015}$/tonne avoided over 30-year project lifetime (at 6 % WACC). This is still higher than current CO_2 price level in Europe. However, with CO_2 price of 20 €/tonne throughout the project lifetime, the CO_2 -DISSOLVED concept has 60 % chance of being profitable in the low scenario while only 10 €/tonne is required for the High scenario.

If some revenues are claimed from CO_2 storage (currently not the case in the EU ETS framework for the CO_2 not issued from hydrocarbon combustion), the NPV of the CO_2 -DISSOLVED concept is better than the pure geothermal project.

This conceptual study shows that the CO_2 -DISSOLVED concept seems worth investigating for small CO_2 sources or partial capture of the emission. It may contribute to reduce CO_2 emission at significantly lower costs than CCS in the specific conditions including CO_2 availability and a favourable subsurface context (geothermal and storage).

6.4 Conclusion

CO_2 -DISSOLVED acts as a complementary technology to traditional CCS approaches and enlarges the potential of CCS for small or medium industrial emitters. This innovation enriches the portfolio of CCS combinations such as BECCS (BioEnergies and CCS). It helps then to overcome the current debates CCS versus renewable energies, showing a large gradient of situations. According to the Multi-Level Perspective (MLP) of sustainable transition, CO_2 -DISSOLVED could contribute to the transformation of the existing socio-technical system, and to its reconfiguration towards renewable sources of energy. As other competing technologies, it could play a rising role in the modification of the energy system. Then, focusing only on CCS implemented on large-scale emitters constitutes a narrow vision of CCS potential in the sustainable transition.

7 Swing Injection

To achieve increased storage capacity in reservoirs and better sweep efficiency, innovative compositional, temperature and pressure swing injection techniques have been developed. These patented methods have been simulated using Sleipner and Snøhvit-based reservoirs and the outcome of these studies show that increased storage and sweep efficiency, in addition to pressure control, can be obtained by applying these methods, in combination with intelligent well design, monitoring technologies and reservoir characterization (Nazarian, 2013 & 2014).

7.1 Concept Description

The idea behind Swing Injection Technology is to actively control the CO_2 plume behaviour, a technique called *Active Plume Management*.

Høier and Nazarian (2010) have developed three technologies, compositional, temperature and pressure swing injection, for stabilising the CO_2 injection front in a saline aquifer, which resembles WAG in hydrocarbon reservoirs. Swing injection technology allows plume control because more pore space is utilised for CO_2 storage and in the case of CO_2-EOR a better sweep efficiency is achieved (Figure 10). The injected CO_2 blend is designed to resemble cycles of liquid-like and gas-like injection.

By changing any of composition, temperature or pressure the thermodynamic equilibrium can be altered and by doing so the injected CO_2 phase can be used to obtain the desired gas or liquid like behaviour.

The gravity number describes the relative dominance of gravitational and viscous forces in the reservoir. It can be used to assess the expected behaviour of CO_2 injection in a saline formation by determining the extent of gravitational override. The swing injection technologies aim to reduce the gravity number during injection by increasing CO_2 viscosity and decreasing the density difference between brine and CO_2. This will result in a more centralised plume around the injection point and reduce the spreading and upward migration of the plume. To verify the proposed techniques, compositional and thermal models have been built based on realistic geological models of the Utsira Formation into which the CO_2 at Sleipner is injected.

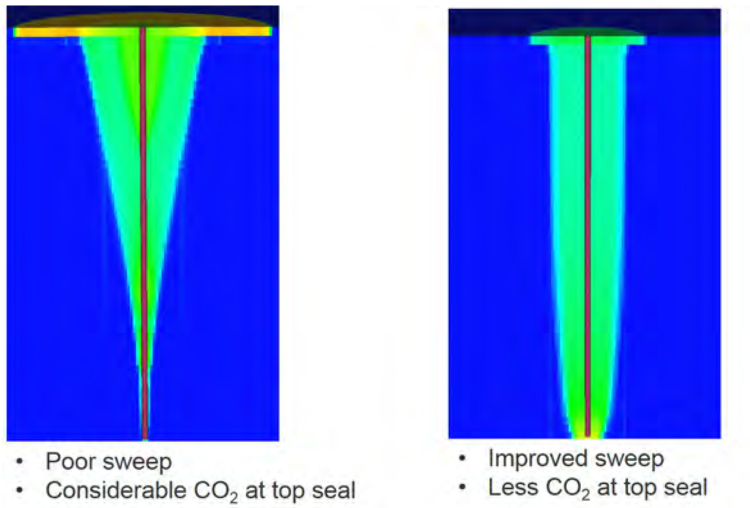

Figure 10: Active plume management means to change the plume shape from the figure to the left to the figure to the right, which will maximize the storage capacity

7.2 Compositional Swing Injection (CSI)

To alter a multi-component fluid system, the composition can either be changed by introducing an extra component or by changing the ratio of components in the system, resulting in a different critical point for the mixture. The effect of doing this can be quite substantial since the new mixture can exhibit totally different behaviour with respect to phase and mobility behaviour.

Introducing an extra component in the form of various hydrocarbon components, could be costly. To make the CSI method affordable it has been proposed to use CO_2 soluble polymers instead of hydrocarbons (Nazarian & Ringrose, 2014).

As an example of how CSI works, consider two different compositions A and B. Composition A represents a typical CO_2 rich injection stream and composition B is generated by changing the total composition (Nazarian *et al.* 2013). Composition A will exhibit gas-like behaviour under reservoir conditions whereas composition B will exhibit liquid-like behaviour (Figure 11).

The two compositions can be injected in cycles to create a gas-like slug chasing a liquid-like slug and thereby stabilising the front. Injection of composition A only would result in a “V-shape” type of plume. Cyclic injection of compositions A and B will result in a more “U-shaped” plume as shown in Figure 10 and thereby increase the utilised pore space.

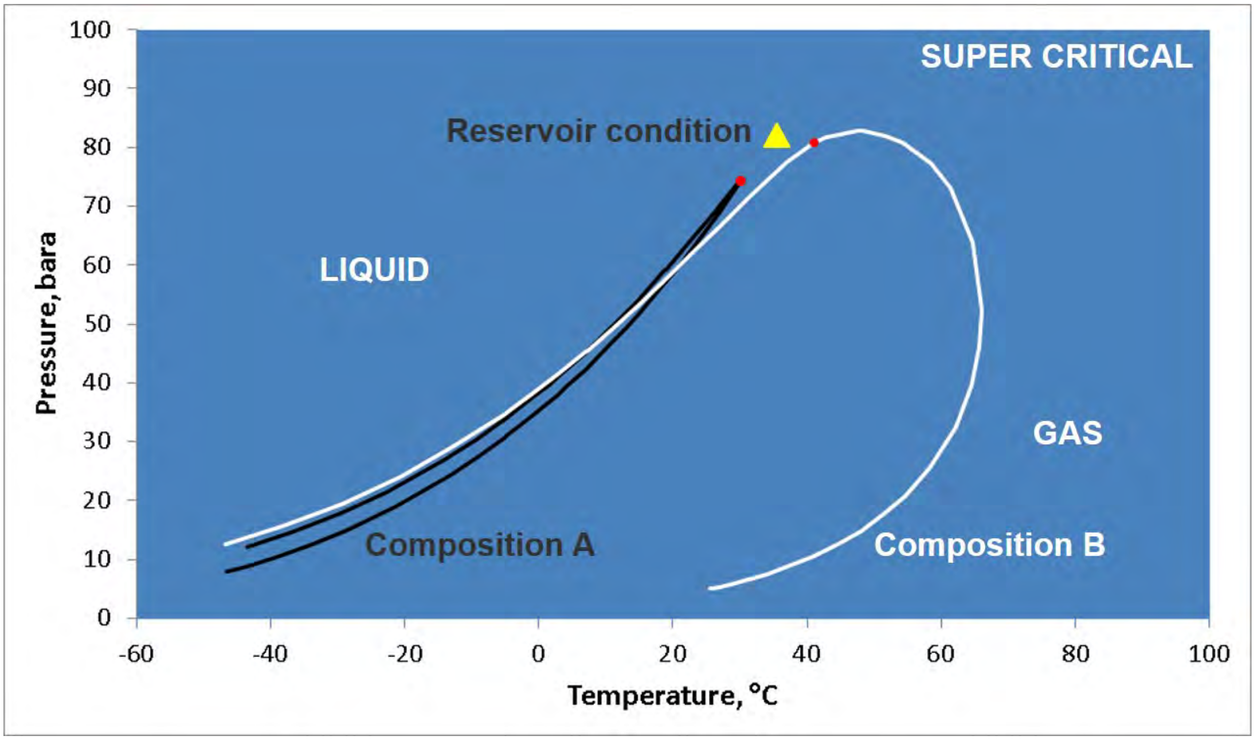

Figure 11: Change of the total composition of the injected stream by adding a new component or by varying the mole fraction of existing components a liquid-like or gas-like behaviour can be achieved at reservoir condition. Composition A is a typical CO_2-rich stream. Composition B is generated by changing the total composition. As can be seen, the position of the critical point is changed. Consequently, while Composition A exhibits a gas-like behaviour under the given reservoir condition, Composition B exhibits a liquid-like behaviour.

7.3 Temperature Swing Injection (TSI)

Temperature changes can also change the thermodynamic equilibrium in a multi-component mixture without changing the mixtures composition. As illustrated in Figure 12, a mixture will show liquid-like behaviour at 20 degrees Celsius, whereas the same mixture at a temperature of 60 degrees Celsius will show gas-like behaviour at the same pressure. The TSI injection concept involves cyclic injection of CO_2 streams at different initial temperatures to achieve the gas-like and liquid-like behaviour.

7.4 Pressure Swing Injection (PSI)

Altering the pressure of the injection stream will also cause a shift in the phase equilibrium as illustrated in Figure 13. Pressure change is, however, directly related to temperature and compositional variations. By changing the temperature, density variations of the injection stream will arise and result in a different hydrostatic head in the injection well, which also will result in a variation in injection pressure. Compositional changes of the injection stream will have a similar effect. The studies performed so far have only demonstrated the effect of TSI and CSI; however, PSI is assumed to have a similar effect (Nazarian *et al*. 2013). More likely, the effects could in practice be combined as a hybrid swing injection.

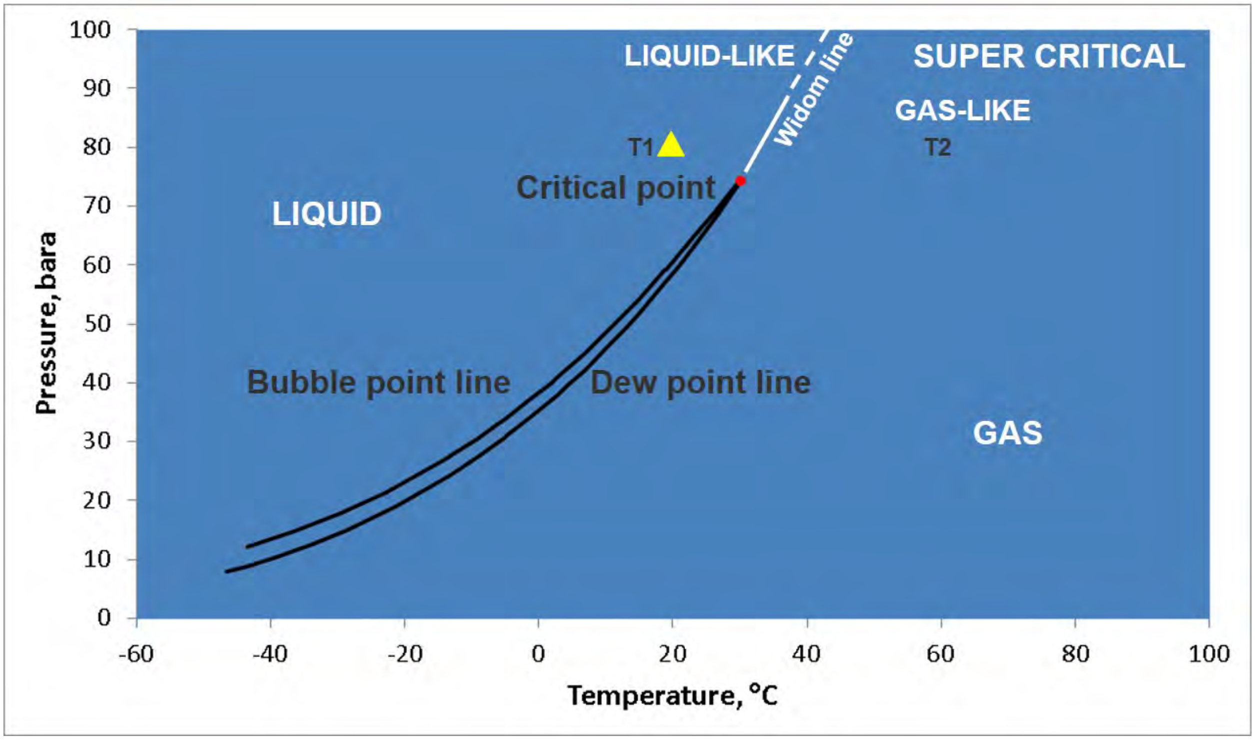

Figure 12: Modification in properties can be achieved by cyclic change of the injection temperature. A typical injection stream demonstrates a liquid-like behaviour in state T1 and gas-like behaviour at state T2.

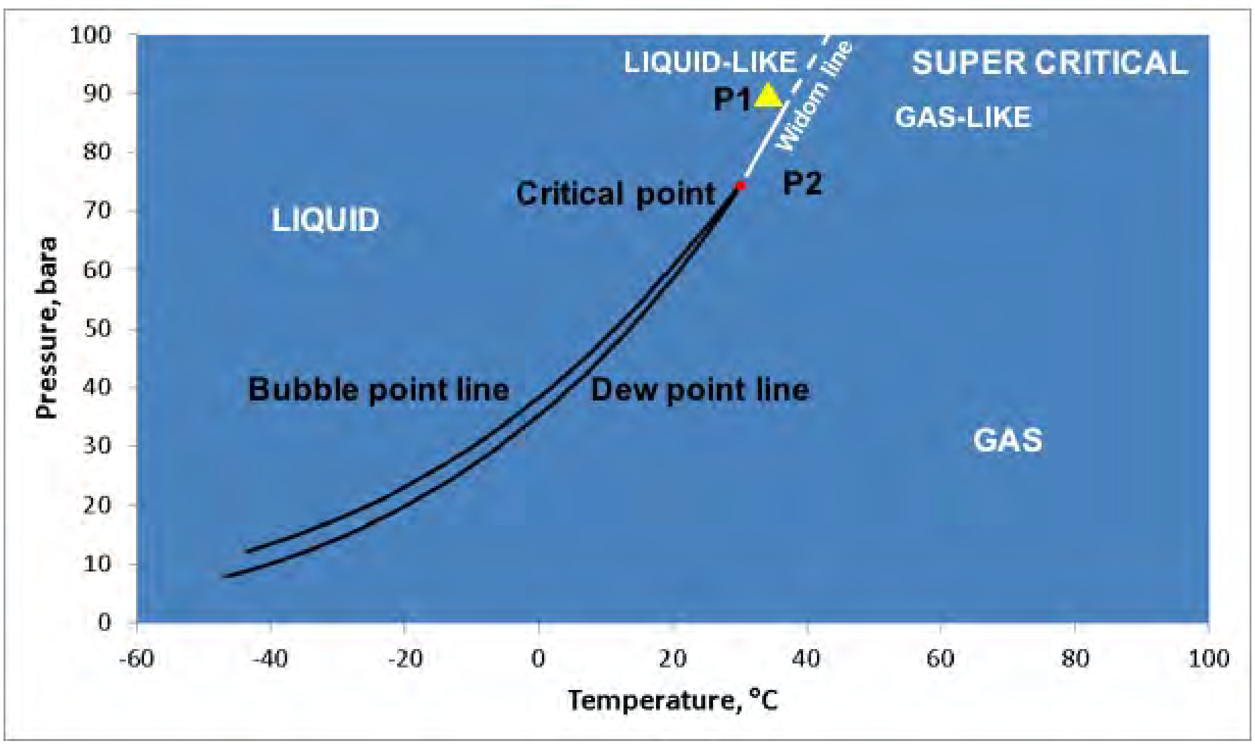

Figure 13: For the same typical CO_2 composition, the injection pressure can be changed between states P1 and P2 so that the injected stream demonstrates liquid-like and gas-like behaviour at the injection point.

7.5 Quantitative Analysis of Active Plume Management

As mentioned earlier, the effect of the CSI and TSI techniques can be described in terms of the gravity number, as shown in Table 2. Application of the CSI and TSI methods can reduce the gravity number by 33% and 35% respectively. However, temperature dissipation within the reservoir reduces the effect of TSI with respect to increased storage capacity (5%) compared to CSI, which increases storage capacity by around 62%.

Table 2: The CSI technique results in around 30% reduction in gravity number. The volume of the reservoir cells touched by CO_2 will reduce by around 60%. TSI has the same effect on gravity number. This means that TSI can modify the properties of the injected stream.

Case	Gravity number N_{gv}	Plume volume Rm^3
Constant composition injection	8.43×10^{-3}	9.52×10^{10}
CSI technique	5.64×10^{-3}	3.51×10^{10}
Percent difference	33.1	61.5
Constant temperature injection	7.21×10^{-3}	2.02×10^{10}
TSI technique	4.67×10^{-3}	1.92×10^{10}
Percent difference	35.2	5.0

Figure 14 illustrates these differences in plume behaviour based on the Sleipner model and comparing between injecting a CO_2-rich stream into the reservoir (Figure 14a) and the model where the CSI technique has been applied (Figure 14b). The injection rate is 1 Mt per year and duration is 30 years. In case A, with the CO_2-rich injection stream, a considerable amount of the CO_2 has reached the top seal and spread out, although some of the CO_2 is retained by intra-reservoir barriers. The plume which is generated after applying CSI is significantly different with an overall reduction in plume spreading both laterally and vertically.

It is also possible to combine the different parameters to obtain swing injection for a given situation. Combining the parameters can be used to minimise the magnitude of parameter modification for the controlling parameters.

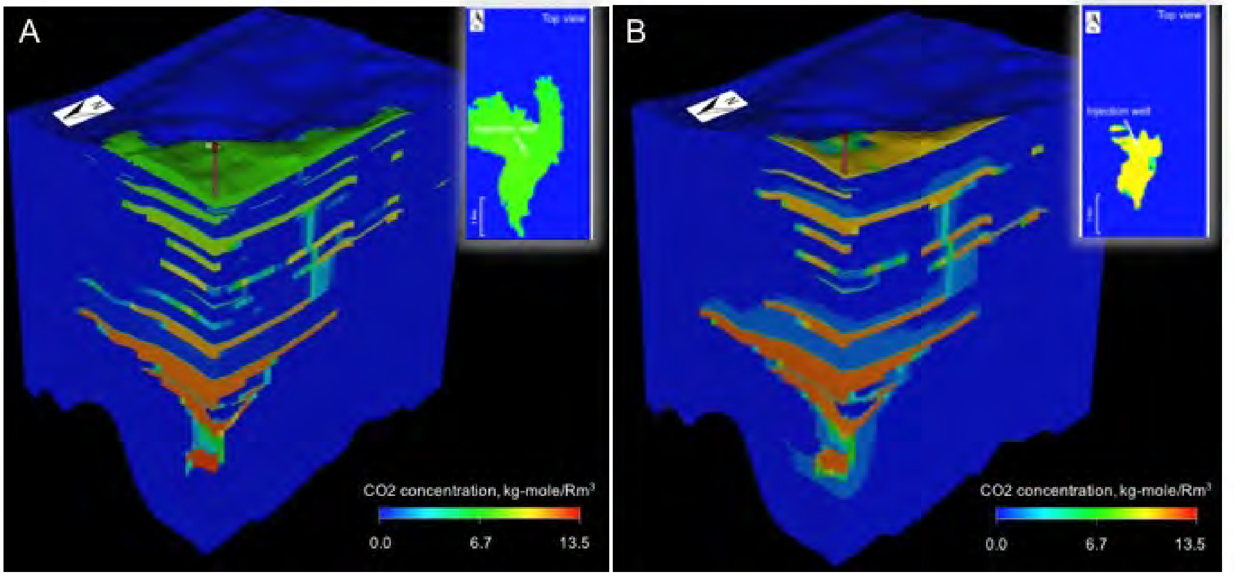

Figure 14: Figure illustrating the difference between modelled behaviour of CO_2 injection with and without CSI technique.

7.6 Well Design for Optimum Utilisation of Swing Injection Technologies

Well design plays an important role for maximising capacity in the reservoir. If injection takes place in a depleted oil or gas reservoir the CO_2 injectivity can be estimated from the production history of the field. If CO_2 is injected into a saline aquifer the reservoir properties are less well known and both injectivity and reservoir communication are much more uncertain. In such a situation, a standard vertical injection well cannot guarantee either the injectivity or the required pore space capacity. In industrial scale projects like Sleipner, Snøhvit or In Salah or demo projects like Ketzin and Decatur-Illinois, injection rates can be considered moderate. High injectivity and high pore space availability is crucial when new projects require high injection rates and capacity and under such circumstances vertical wells might not be the right solution.

Instead of using a vertical well, a *horizontal, multi-branch well* has been modelled using a reservoir resembling the Snøhvit Tubåen Formation (Nazarian *et al*. 2013). In this study, a horizontal well design has been shown to be a better alternative to a vertical well avoiding early pressure build-up and utilising more pore space. The aim of the study was not to control the vertical plume movement but to enhance injectivity.

8 Ranked Technique Effectiveness & Technique Status

With the growing challenge to rapidly ramp-up the volume of CO_2 storage to meet the 2,400 Mtpa target by 2035, all technologies are likely to represent strong value to the optimisation of site storage operations. All of the techniques examined have been considered from a TRL (Table 3). A summary of each technology is found in **Table 4**.

Table 3: Technology Readiness Levels (TRLs) in the Project Lifecycle", Ministry of Defence website www.aof.

Technology Readiness Level	Description
TRL 1	Basic principles observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Technology basic validation in a laboratory environment
TRL 5	Technology basic validation in a relevant environment
TRL 6	Technology model or prototype demonstration in a relevant environment
TRL 7	Technology prototype demonstration in an operational environment
TRL 8	Actual Technology completed and qualified through test and demonstration
TRL 9	Actual Technology qualified through successful mission operations

8.1 Polymers, Surfactants & Foams

Techniques from the hydrocarbon sector, focused on improved oil sweep in EOR operations, are reasonably mature, and are likely to only require some minor laboratory and modelling work specific to the use of CO_2 rather than water or methane as the injectant, before trialling in field. The effectiveness of these techniques would be highest near the injection well; how effectively these solutions apply far field (e.g. for a large saline aquifer) would need to be considered.

The use of these polymers and surfactants to access lower permeability zones and limit lateral spread does appear to strongly align to pore space utilisation in CO_2 storage. As these two technologies require additives to the injected volume of CO_2, a cost analysis would be needed relative to the 10s of Mt of CO_2 being injected.

Foams, having a nearer wellbore effect than polymers and surfactants, may be a cheaper option to consider. The application of foams block high permeability pathways, thus preventing long fingering of CO_2 and creating large regions for monitoring. However, this application removes access to some of the pore space. Further investigations are therefore recommended to consider the best way to use this technique.

8.2 Pressure Management

Pressure management has, because of hydrocarbon production and EOR operations, been tested at commercial scale. However, this application has not been performed in CO_2 storage activities, either as a risk reduction technique or for the purposes of optimising the use of pore space. Pressure relief wells are being considered for future CCS projects, and active pressure relief has been included as part of the operation for the Gorgon CO_2 Storage Project. It will become important to gain learning from this project, as well as the broader application of pressure relief for the purposes of pore space optimisation.

Understanding the behaviour of stored CO_2 in heterogeneous reservoirs will be key to testing the effectiveness of increased injection pressure for improving CO_2 sweep. Given that the essentially all reservoirs are heterogeneous to a degree, it is important to gain a detailed understanding of capillary processes during CO_2 injection and plume migration. The approach adopted by the GeoCquest project is a good example of the type of activity required to then consider how to enhance pore space utilization, with their ultimate aim is to apply their workflow at a commercial scale site that typically will be in a heterogeneous sandstone. Their investigations to date suggest that rock heterogeneity at all scales enhances trapping.

8.3 Microbubble CO_2 Injection

The concept of microbubble CO_2 injection for higher pore space utilisation shows very high potential to high sweep efficiency in both direct CO_2 storage operations and in a CO_2-EOR operation. Laboratory analysis already conducted has shown the potential benefit on Berea sandstone and Japanese oil field core samples, and modelling results show microbubble CO_2 migrating more slowly and with improved spread relative to normal-size bubbles. Further, this technique shows a rapid level of dissolution of the CO_2, which utilises the existing formation fluids more effectively and improves the long-term containment of the injected CO_2.

This technique, validated in models and laboratory, needs to be trialled at a field scale.

8.4 CO_2 Saturated Water Injection and Geothermal Energy Production

The use of pre-dissolved CO_2 provides a good example of pairing a complementary technology to traditional CCS approaches, to apply the use of CCS for small or medium industrial emitters.

This technique would have niche opportunities in the improved pore space utilisation area yet can help enable the ramp up of CCS by its complementary technology nature. For this technique to be considered commercially, the PI-CO_2 technology at lab scale would require trial at a field scale.

8.5 Swing Injection

Swing injection through changing the composition, temperature and/or pressure allows the thermodynamic equilibrium to be altered so that injected CO_2 can have modified flow properties. With changes in these properties resulting in reduced buoyancy, improved sweep and limited lateral spread, they present strong candidates for improving a CO_2 storage operation's pore space utilisation.

The described technology has been through the modelling stages and is at present considered to be at TRL 3.

Table 4: Comparison table of pore space utilisation technologies. Technologies are ranked in order of priority (column 'P') for continued technology maturation. Green indicates high perspectivity for the technology, light green less urgency, while orange indicates lower technology prospectively broadly, yet strong niche opportunity.

P	Technology Type	Prior R&D and application	Technology Readiness Level (TRL)#	Technology Prospectively	Core Recommended Action
1	Microbubble CO_2 Injection	Laboratory and Modelled, prototype	TRL 4	High potential	Trial at in field research facility
2	Swing Injection	Laboratory and Modelled	TRL 3	High potential	Validate technology at lab scale
3	Increased Injection Pressure	Laboratory and Modelled	TRL 3	High potential	Validate technology at lab scale to assess sweep effectiveness in heterogeneous reservoirs
4	Active Pressure Relief (increase sweep & reduce lateral spread)	EOR, planned for Gorgon CO_2 injection project	TRL 6	High potential	Pressure relief - Key lessons drawn from active commercial project using pressure relief wells as a risk mitigation technique
5	Foams (block high permeability pathways)	EOR	TRL 6	Reasonably well understood	Modelling of application effectiveness prior to Demonstration at commercial scale
6	Passive Pressure Relief	Modelled	TRL 4	Limited effectiveness	Trial at field research facility. Consideration around long-term fluid management
7	Polymers (increase formation water viscosity)	EOR	TRL 7	Reasonably well understood	Cost effectiveness investigations. Demonstration at commercial scale*
8	Surfactants (reduce residual saturation of formation water)	EOR	TRL 7	Reasonably well understood	
9	CO_2 saturated water injection & geothermal energy	Laboratory and Modelled	TRL 3	Site specific & lower volume	Seek opportunity to trial PI-CO_2 technology at lab scale

* minor modelling and laboratory investigations may be required prior to commercial scale application

See technology readiness chart

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9.1 Glossary of terms

Term	Definition
°C	Degrees Celcius
BECCS	Bio Energy and CCS
CO_2-EOR	CO_2 Based Enhanced Oil Recovery
CSI	Compositional Swing Injection
CT	Catscan
EM	Electromagnetic
EOR	Enhanced Oil Recovery
FCFS	First Come, First Serve
IOR	Improved Oil Recovery
ISO	International Organisation for Standardisation
MLP	Multi-Level Perspective
µm	Micrometre (1/1,000,000 metres)
Mpa	Mega Pascal
Mt	Million Tonne
MTS	Mass Transfer System
NPV	Net Present Value
PSI	Pressure Swing Injection
PV	Pore Space Volume
R&D	Research and Development
SEM	Scanning Electron Microscope
t	Tonne
TRL	Technology Readiness Level
TSI	Temperature Swing Injection
UGS	Underground Storage
WACC	Weighted Average Cost of Capital

CARBON SEQUESTRATION LEADERSHIP FORUM TECHNICAL GROUP

Task Force on Clusters, Hubs, and Infrastructure and CCS Results and Recommendations from "Phase 0"

April 2019

”CCUS infrastructure is key to unlocking huge clean growth potential in the UK and can contribute to a cost-effective pathway for reducing UK CO_2 emissions”

(**UK CCUS Cost Challenge Taskforce Report July 2018)**

The Five Keys to Unlock CCS Investment. No.4: ”Build CO_2 networks and accelerate CO2 storage assessments in key regions.”

(IEA https://www.iea.org/media/topics/ccs/5KeysUnlockCCS.PDF)

1. Background

1.1. CSLF Technology Group recommended target and strategy

The CSLF Technology Roadmap 2017 (TRM) recommends that the CSLF Ministers adopt the following target for CO_2 storage by 2025 to keep the global temperature increase from anthropogenic CO_2 emissions to 2°C or below:

Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) CO_2 per year by 2025 (or have permanently captured and stored of 1,800 Mt CO_2).

To achieve this the TRM recommends ten strategic actions that are deemed necessary, of which the following four are regarded to fall under the Technical Group’s responsibilities:

- Facilitate CCS infrastructure development.
- Leverage existing large-scale projects to promote knowledge-exchange opportunities.
- Drive costs down along the whole CCS chain through RD&D.
- Facilitate innovative business models for CCS projects.

The TRM puts obligations on the Technical Group to, trough its Projects Interaction and Review Team (PIRT):

- Monitor the progress in CCS in relation to the Recommended Priority Actions.
- Report the findings at Ministerial meetings.
- Suggest adjustments and updates of the TRM.

1.2 Task Force objectives and mandate

At the CSLF Technical Group (TG) meeting in Melbourne, Australia, 17 October 2018, it was decided to establish a task force on Clusters, Hubs, and Infrastructure. This task force will conduct only preliminary “Phase 0” activities to review progress made on the topic since the CSLF Technology Roadmap 2017 (TRM) was issued. The task force will present a recommendation on whether or not to continue past the preliminary phase at the next Technical Group meeting.

Task force members for the preliminary phase are Norway (lead), Australia, Brazil, Canada, and the United Kingdom.

Topics that could be addressed by the task force include:

- Brief review of networks, existing or in construction
- Identifying and reviewing projects that have moved forward toward technically and financially
- Identifying and reviewing new studies and concepts

- Identifying and reviewing publications that aim to progress the implementation of CCUS networks

Thus, this note addresses the progress of the first of the strategic actions.

1.3 Some definitions

It is useful to have a common understanding of the concepts discussed in this note. Here follow some definitions.

Cluster From GCCSI, 2016)

- An industry cluster is a geographic concentration of interconnected businesses, suppliers, and associated institutions in a particular field. Clusters can emerge for many different reasons, including proximity to raw materials, to transport options such as ports, to labour supply, and to markets.

Hub (from GCCSI, 2016)

- CCS hubs are the central collection or distribution points for CO2. One hub would service the collection of CO_2 from a capture cluster or distribution of CO_2 to a storage cluster
- Hubs could be located at the capture end or the storage end of a multi-user pipeline (forming capture/collection or storage hubs), or both.

Network (from GCCSI, 2016)

- A CCS hub and cluster network (network for short) brings together many of the elements along the CCS value chain (CO_2 source, capture, transport, injection, storage) with multiple co-located (clustered) source capture facilities (of the same or different types) supplying CO_2 to a shared ‘oversized’ transport and storage system.

Infrastructure

- The physical parts of the network (single or shared capture facilities; temporary storage facilities; injection facilities, pipelines, ships)

Note that the definitions apply onshore as well as offshore.

Note also that according to these definitions, a plant or facility can be part of network without being part of a cluster.

1.4. Existing and in construction networks

Based on IEAGHG (2015), GCCSI 2016), and indirectly COCATE (2013), the TRM identified 12 cluster and hub locations (Figure 1), including three existing networks in USA and one in construction in Canada, as well as initiatives or plans for CO_2 networks in Australia, Europe (the Netherlands and the United Kingdom), and the United Arab Emirates. In Europe, several studies had identified CCS hubs or infrastructures. For example, ZEP (2013, 2016, 2017); Jakobsen et al. (2017); Bellona (2016); and Brownsort, Scott, and Hazeldine (2016), the last by reuse of an existing oil pipeline.

1.4.1. United States of America and Canada: Onshore networks

Three networks are in operation in USA - the Denver City (inception 1985), Gulf Coast (inception 1999), and Rocky Mountain (inception 1986) hubs - all in the United States. These are CO_2-EOR systems where clusters of oilfields are fed by a network of pipelines. The Alberta Carbon Trunk Line, Canada, was, and still is (early 2019), in construction (Figure 2).

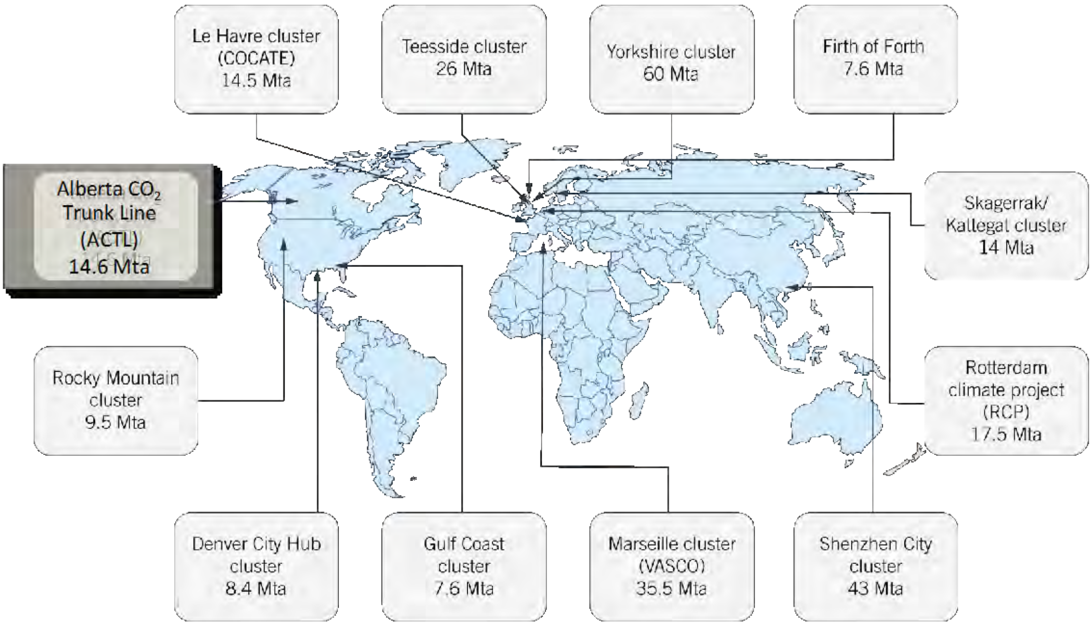


Figure 1. Some Industrial clusters, from GCCSI (2016, adapted from IEAGH, 2015, and ZEP, 2014)

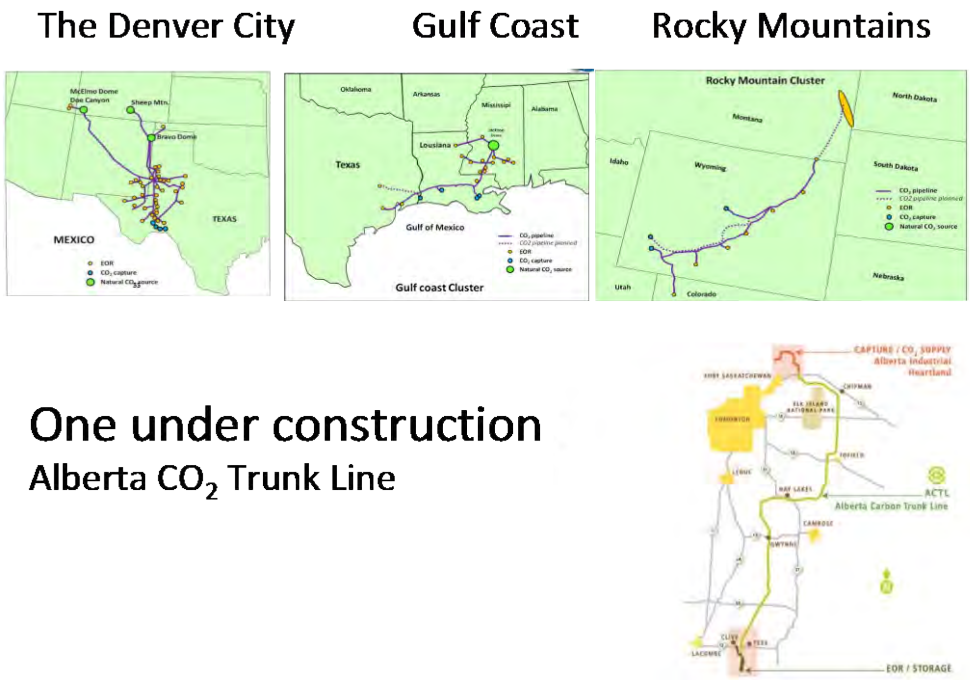


Figure 2. Operational and in-construction CCUS networks in North America

1.4.2. Brazil: An offshore CCUS network

The Petrobras project “Offshore Pre-Salt Santos Basin project” can be classified as a “CCUS hub and cluster network”. Here, a set of FPSOs unit that incorporates CO_2 separation and injection facilities, specifically, CO_2 capture from natural gas and reinjection system for enhanced oil recovery (EOR) purposes (Figure 3).

1. For the offshore pre-salt Santos Basin development, the Petrobras has committed to avoiding CO_2 venting to the atmosphere in natural gas production operations. In 2014 Petrobras and its partners have started offshore EOR CO_2 injection at Lula oil field, located in the Santos Basin ca. 300 kilometres of Rio de Janeiro coast.
2. CO2 reinjection: Currently, this process is carried out by nine FPSOs using membrane permeation modules for CO_2capture. In December 2017, Petrobras reached the milestone of 7 MM tonnes of CO_2 separated from natural gas and re-injected in the Santos Basin Pre-salt - for enhanced oil recovery (EOR) purposes.
3. The CO_2 cumulative injection is estimated to reach the milestone of 40 MM de ton of CO_2 separated from natural gas and re-injected in the Santos Basin Pre-salt by 2025.

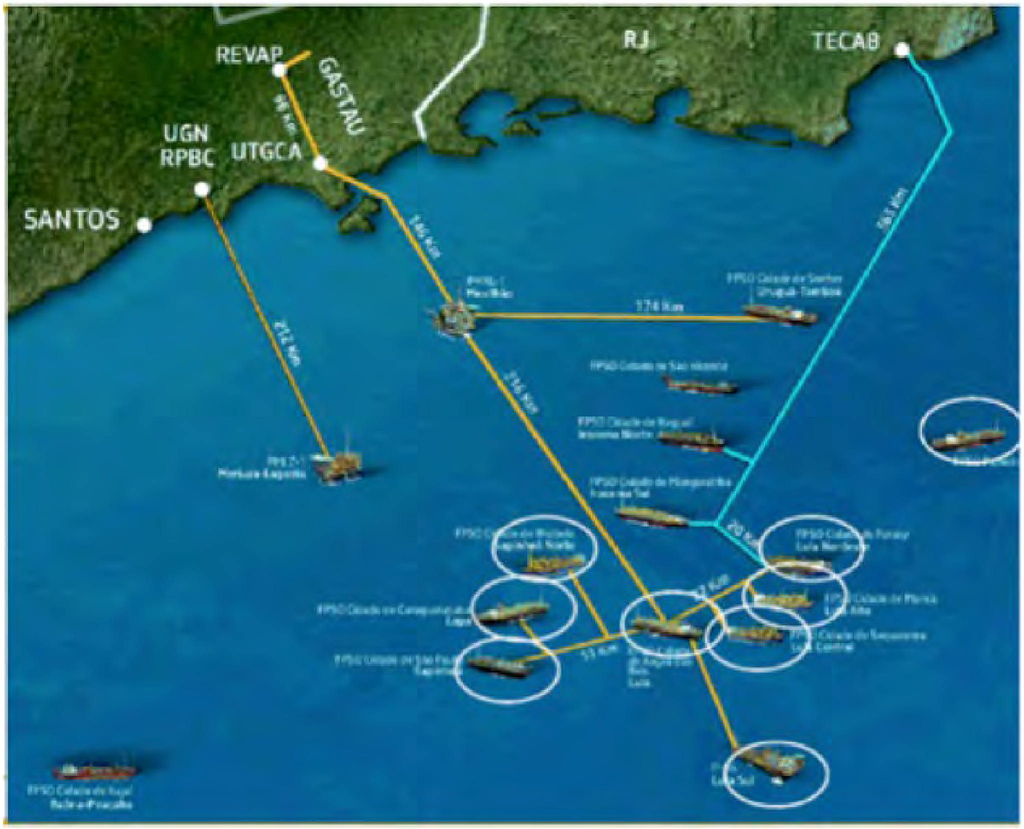


Figure 3. The network FPSOs with CO_2 separation and injection facilities for enhanced oil recovery (EOR) in the Santos basin, offshore Brazil. Courtesy: Grava, W.M. 2018. "Technology for Offshore Gas Production". The 4th Brazilian Congress on CO2 in the Oil, Gas and Biofuels Industries, Rio de Janeiro.

1.5. Importance of clusters, hubs and infrastructure

The TRM summarises several potential benefits of developing hubs and infrastructure for clusters of CO_2 sources form several sources, including GCCSI (2016), ZEP (2013), and IEAGHG 2015):

- Cost sharing
  - Lowering costs in building early infrastructure by utilizing benefits of connecting low-cost industrial sources with storage sites.
  - Distributing investment and operational costs by sharing infrastructure, i.e. the cost per unit CO2 transported will be lowered.
- Lowering the entry barriers for participating CCS projects, such as emitters with small-volume sources and emitters with limited or no access to local storage.
- Securing sufficient and reliable CO_2 for CO_2-EOR and other CO_2 utilisation projects, which is likely to be an important element of some clusters because of the revenue it can contribute.

- Minimizing the environmental impacts associated with infrastructure development, as well as the impact on communities.
- Minimizing and streamlining efforts in relation to planning and regulatory approvals, negotiations with landowners, and public consultations.
- Sharing and utilizing surplus heat in the capture processes of industrial clusters.

The Norwegian Full Scale Project can serve as an example of the cost benefits of a CCS network. Osloeconomics and Atkins (2016) showed cost per tonne CO_2 stored for the network described below in Section 2.2.1 for one, two and three industrial sources in southeast Norway, with a common fleet of ships for transport to terminal at the Norwegian west coast and common pipeline transport to offshore storage. The network solution with all three sources was estimated to be 18 -41 % cheaper than from a single source, depending on the amount of CO_2 captured at the single source.

The United Kingdom CCS Cost Reduction Task Force (CCSA 2013) found that CO_2 transport costs could be reduced by more than 50% with the deployment of large and efficiently utilized pipelines.

Transportation of CO_2 represents a smaller part of the total costs for a CCS chain than capture. The impact on the total cost of a CCS chain may be moderate, particularly for onshore pipelines (IEAGHG 2015). However, the cost may be significant in absolute money terms (Roussanaly, Brunsvold, and Hognes 2014).

Most gaps, risks, and challenges are commercial and political in nature and may 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, flexibility, reliability, financing and political aspects, and last but not least, lack of business models for larger CCS systems. Some thinking on business models has started that includes the separation of CO_2 capture at the sources from the transport and storage parts (Esposito, Monroe, and Friedman 2011; Pöyry and Teesside Collective 2017; Banks, Boersma, and Goldthorpe 2017; Norwegian Ministry of Petroleum and Energy (MPE), 2016; Element Energy, 2018a,b; Pale Blue Dot, 2018; UK Government, 2018).

1.6. TRM Recommendations on clusters, hubs, and infrastructure

Based on the above, the TRM made the following recommendations (quotes):

1.6.1. Priority Recommendation to decision makers

Facilitate CCS infrastructure development

1.6.2. Specific recommendations for CO_2 hubs and clusters

Governments and industry should work together to:

<u>Towards 2020:</u>

- Design and initiate large-scale CO_2 hubs that integrate capture, transport, and storage, including matching of sources and sinks.
- Develop commercial models for industrial and power CCS chains.

<u>Towards 2025:</u>

- Implement the first large-scale (i.e., >10 Mt CO_2/year aggregate throughput) CCS chains in power, industrial, and bio-CCS. These should be focused in industrial regions that have the potential to share infrastructure, rather than focusing on individual projects.
- Implement initial shared infrastructure for a limited number of plants within industrial clusters. This should recognize that in the initial phases, volumes within these clusters may be less than one million tonnes per annum, but that expansion from this initial start will occur.

<u>Towards 2035:</u>

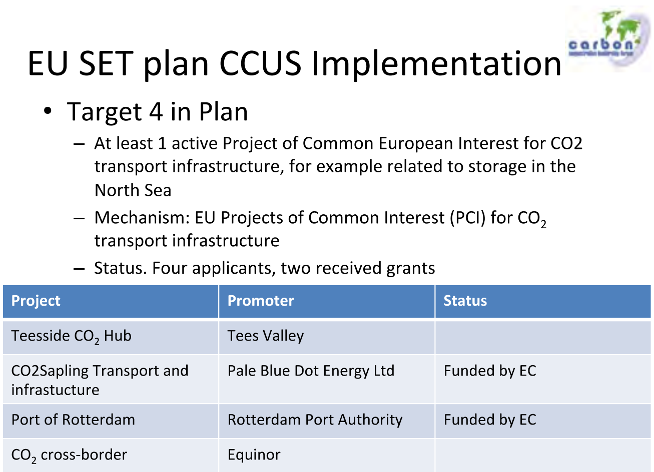
- Continue progressive rollout and expansion of full-scale CCS chains and clusters in power, industrial, and bio-CCS. This includes large-scale CO_2 transport networks that integrate CO_2 capture, transport, and storage, including matching of sources and sinks. 3. CCUS Infrastructure/Networks Projects that passed a milestone or were secured funding summer 2017 – end 2018.

2. CCUS Infrastructure/Networks Projects not in the TRM

2.1. Europe

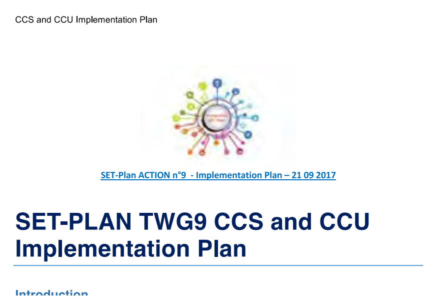
2.1.1. The European Commission SET Plan – Projects of Common Interest (PCI)

Projects of common interest (PCIs) are key cross border infrastructure projects that link the energy systems of EU countries. They are intended to help the EU achieve its energy policy and climate objectives: affordable, secure and sustainable energy for all citizens, and the long-term decarbonisation of the economy in accordance with the Paris Agreement. CCS and CCUS targets and ambitions of the European Commission are outlined in the document Strategic Energy Technologies (SET) Technical Working group (TWG) 9 implementation plan. Several industrial clusters are mentioned. Four were shortlisted and two have been funded.


EU SET plan CCUS Implementation

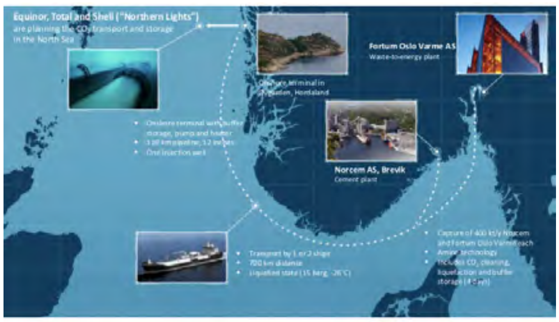
- Target 4 in Plan
  - At least 1 active Project of Common European Interest for CO2 transport infrastructure, for example related to storage in the North Sea
  - Mechanism: EU Projects of Common Interest (PCI) for CO_2 transport infrastructure
  - Status. Four applicants, two received grants

Project	Promoter	Status
Teesside CO_2 Hub	Tees Valley	
CO2Sapling Transport and infrastucture	Pale Blue Dot Energy Ltd	Funded by EC
Port of Rotterdam	Rotterdam Port Authority	Funded by EC
CO_2 cross-border	Equinor	



2.1.2. A Norwegian CCUS network

The Norwegian Full Scale project involves CO_2 capture at one cement factory at Brevik (ca. 150 km south of Oslo) and one waste-to-energy plant in Oslo. The CO_2 will be transported by ship to a hub/CO2 storage terminal on the west coat of Norway and from there by pipeline to a storage site in the North Sea. The project describes what can be considered a CCS network. The cement plant is part of an industrial cluster but so far the only facility that will take part (a nearby fertilizer plant was involved in the pre-studies buy is no longer part of the project).



The project was granted funds for Front End Engineering Development (FEED) in 2018 and the plan is to reach a final investment decision (FID) in 2020/21. The industrial plants as well the Norwegian government and consortium of oil companies contribute to the funding.

For more information, see MPE (2016) and Carepenter (2019).

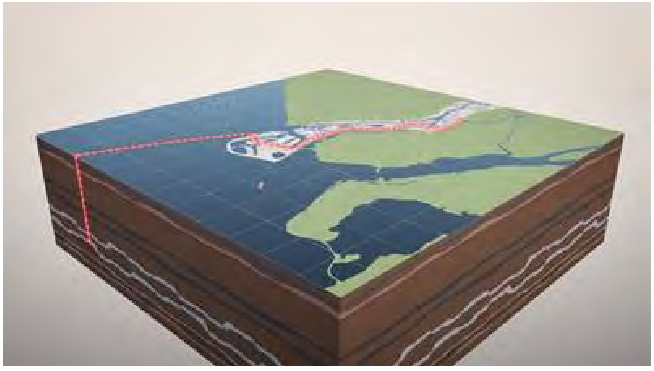
2.1.3. A CCUS Network in the Netherlands

The Port of Rotterdam CCUS Backbone Initiative (Porthos) aims to develop basic infrastructure to collect captured CO_2 from various industrial sources in the Rotterdam port area and transport it to the North Sea for storage.

The Porthos project was granted € 6.5 mill. by the European Commission as a Project of Common Interest (PCI) as well as receiving funds from industry.

A feasibility study was completed in April 2018. The project leaders will continue to consolidate the business case and work towards an investment decision in 2019.

For more information, see Port of Rotterdam (GCCSI, 2018).



2.1.4. A UK CCUS network – CO_2Sapling

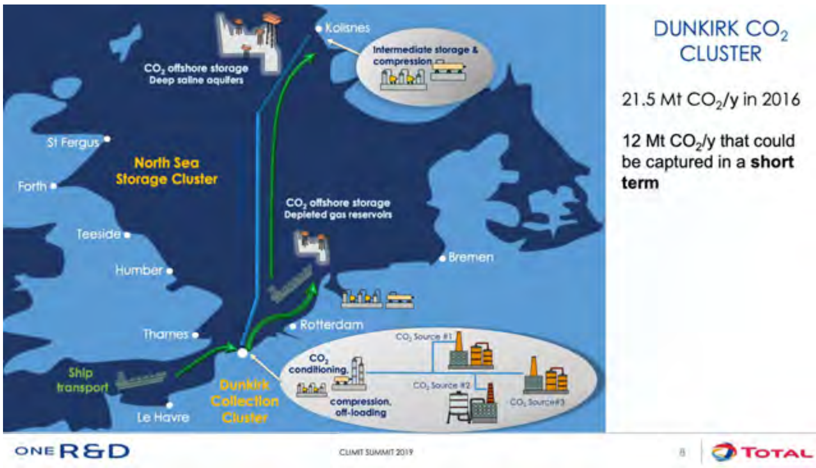
The CO_2Sapling project is a CO_2 transportation infrastructure project that has grown from and will build on the project ACORN, a full chain CCS project in the portfolio of the European programme Accelerating CO_2 Technologies (ACT)

CO_2Sapling was granted € 3 mill. by the European Commission as a Project of Common Interest (PCI) as well as receiving funds from the UK and Scottish Governments and industry in late 2018. The project will work on a feasibility study with the aim to start Front End Engineering Development (FEED) in 2019.

2.1.5. The Dunkirk CO_2 cluster

This network could potentially capture 12 Mt CO_2/year from industrial sources in the Dunkirk area and transport it offshore for storage in depleted gas reservoir or ship it to Kollsnes, the location of the intermediate storage and compression facility of the Norwegian full-scale project. A collection hub at

Dunkirk could also receive CO_2 from other sources by ship before being sent to storage.



Source: David Nevicato, Total CCUS Research Programme Manager, presentation at CLIMIT Summit 2019, Oslo, Norway, 26-27 February 2019 (http://www.climit.no/no/PublishingImages/presentasjoner-fra-climit-summit-2019/David%20Nevicato,%20Total.pdf)3.

2.1.6. Align – an European Commission Network Project

The Align project is an ACT (Accelerating CCS Technologies) project funded by the European Commission and led by the Netherlands. Its goal is to transform six European industrial regions into economically robust, low-carbon centres by 2025. A strong focus of the transport work package is ship transport of CO_2.

2.1.7. Ireland (GCCSI, 2018)

The Ervia Cork CCS project plans capture CO_2 from a number of emission-intensive companies located in Cork, with initial consideration being given to the two modern gas-fired, combined-cycle gas turbine power stations Whitegate and Aghada and Ireland's only oil refining business: Irving Oil Refinery (75,000 barrels per day). The captured CO_2 is planned to be transported via an existing pipe network, which includes 54 kilometres offshore pipeline, to the potential CO2 storage sites in the Kinsale Gas Field.

2.1.8. Clean Gas Project and Teesside Collective

The Clean Gas project will combine CO_2 capture from new efficient low-carbon power generation and local industrial emitters in Teesside. This is led by the Oil and Gas Climate Initiative Climate Investments in a strategic partnership with BP, ENI, Equinor, Occidental Petroleum, Shell, and Total (OGCI CI, 2018)[1]. The infrastructure created would also enable wider industry on Teesside and to capture and store CO2 from their processes (previously proposed by the Teesside Collective). The Teesside Collective project was qualified as EU PCI project, but was not awarded funds in late 2018.

2.1.9. Two UK hydrogen networks

H21 North of England

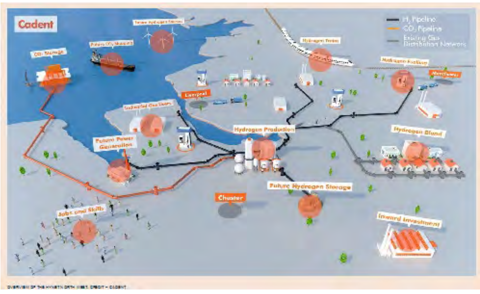
Although a network for distributing hydrogen, H21 is included here as an example of a new gas network that involves CCS.

[1] The OGCI is led 13 oil companies and responsible for a more than $1billion fund, investing in technologies and business models which lower the carbon footprint of the energy and industrial sectors.

The H21 North of England aims to decarbonise power, heat and transport across the North of England. It will convert the UK gas grid from natural gas to CCS decarbonised hydrogen, converting 3.7 million metering points across Leeds, Bradford, Manchester, Liverpool, Hull, York, Teesside and Newcastle. The clean hydrogen will be produced from large- scale production plants with 12.15 GW capacity, with integrated CO_2 capture processes to capture up to 20 Mtpa CO2 by 2035 in several phases. CO_2 storage is planned to be in saline aquifers and depleted gas fields in the Southern North Sea. A feasibility study was submitted to the UK authorities in November 2018.

Hynet

Again a hydrogen network, the HyNet North West is a CCUS-equipped hydrogen production and distribution network developed by the UK gas distribution company Cadent together with Progressive Energy and ENI. The facility will produce hydrogen from natural gas that will then be supplied to industrial sites, to households for heat supply and serve as transport fuel. Natural gas will be converted to hydrogen gas via auto-thermal reforming to supply a core set of major industrial gas users and industrial sites. With this facility, Cadent is developing CCUS infrastructure.



2.2. Australia

2.2.1. CarbonNet

This project is investigating the feasibility for a commercial-scale, multi-user CCS network in Gippsland, Victoria, Australia. It is jointly funded by the Australian and Victorian Governments to 2020, with significant research investment from, among others, ANLEC R&D. Knowledge sharing takes place via GCCSI, and CarbonNet is working collaboratively with industry to secure customers and investors in a CCS service. Feasibility studies completed, project development ongoing with the aim to transit to private sector around 2020/2021. CarbonNet includes plans for hydrogen production in cooperation with Japan.

(http://earthresources.vic.gov.au/earth-resources/victorias-earth-resources/carbon-storage/the-carbonnet-project;

https://www.cslforum.org/cslf/sites/default/files/documents/Melbourne2018/CarbonNet_Project_Presentation_to_Technical_Group.pdf)

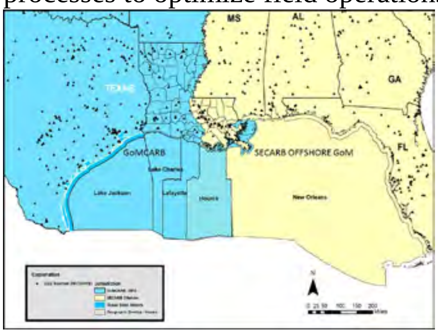
2.2.2. South West Hub

(http://www.dmp.wa.gov.au/South-West-Hub-CCS-1489.aspx; https://www.cslforum.org/cslf/sites/default/files/documents/Melbourne2018/South_West_Hub.pdf)

This is project that so far has focussed on a storage hub in the heart of the industrial area of south west Australia. It is a staged project that involves collecting and analysing data and samples from the Lesueur Sandstone formation, to test its feasibility as a CO_2 reservoir. The South West Hub is a partnership between government and industry. Research into the geo-sequestration is being funded by the Australian Government and the Western Australian Government through the Department of Mines, Industry Regulation and Safety (DMIRS).

2.3. Offshore United States of America

Gulf of Mexico Partnership for Offshore Carbon Storage (GoMCarb) focuses on the assessment of offshore (sub-seafloor) geologic carbon storage beneath the Gulf of Mexico. It will identify CO_2 offshore transport and delivery options, logistics, risks
and regulations in the gulf region, including assessing the feasibility of decommissioning and re-purposing existing infrastructure to facilitate offshore CO_2 storage. Existing infrastructure such as pipelines, platforms, and wells will be assessed, collated, and mapped to the location of potential offshore storage reservoirs. GoMCarb will link source-transport-storage options in the Gulf of Mexico, from transportation from the source of CO_2 to the offshore storage wellhead, and identify processes to optimize field operations, reservoir response, and operation costs. Funded by US DoE.



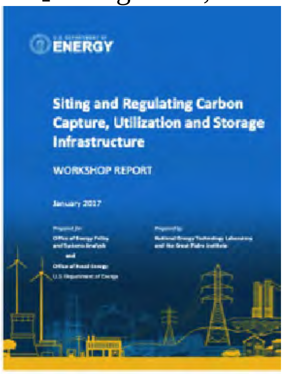
2.4. China

The Sinopec Zhongyuan Oil Company CCUS project, started from April, 2009 may be considered an infrastructure project. CO_2 (capacity of 500,000 t/yr) is captured from Kaifeng, Xinlianxin and Zhongyuan Refining and Chemical plants and transported to an oil field for EOR.

3. Other reports or very early initiatives

US Department of Energy: Siting and Regulating Carbon Capture, Utilization and Storage. Workshop report January 2017 The Department of Energy (DOE) sponsored a technical workshop in April 2016 in Washington, D.C to identify and promote best practices for siting and regulating CO_2 infrastructure (pipelines, EOR, and other geologic CO_2 storage sites). The purpose of the workshop was to foster communication, coordination, and sharing of lessons learned and best practices among states and entities that are involved in siting and regulating CO_2 infrastructure, or that may have CO_2 infrastructure project within their borders in the future.

The scope of the technical workshop also included discussions around regulation and management of CO_2 storage sites, which serve as critical infrastructure for entities capturing CO_2.



IEAGHG, 2018. Enabling the Deployment of Industrial CCS Clusters. IEAGHG Technical report 2018-01. February 2018.

The study included investigation of four different ICCS cluster business models:

- Public transport and storage (T&S) company
- T&S as regulated assets
- Anchor CCS project with 3rd party access
- CO_2-EOR

One finding is that Industrial CCS (ICCS) is not yet commercially mature.

Private investment is likely to occur if the following four key enablers are addressed:

- Mitigate the risk of carbon “leakage”
- Provide the emitters with margin certainty through appropriate subsidies
- Decouple the business cases for capture and infrastructure
- Share the key risks with government through guarantees

The study also found that the necessary level of government support is high. However, without ICCS, governments might need to rely on more expensive solutions to meet decarbonisation targets.

Element Energy 2017. Deployment of an industrial carbon Capture and Storage cluster in Europe: A funding pathway.

This study focused mainly on a possible industrial hub with common transport of CO_2 to an offshore location. Some key messages:

- Industrial CCS clusters are key to European industrial decarbonisation
- The first industrial CCS clusters in Europe can be operational in the early 2020s
- European CCS clusters can be unlocked with grants, subsidies and guarantees
- Member State support and contribution is vital in the short-term
- Important European funds can be made available to industrial CCS clusters
- With government support, European industrial CCS clusters could be fully funded

UK CCUS Cost Challenge Taskforce Report, Delivering Clean Growth. July 2018.

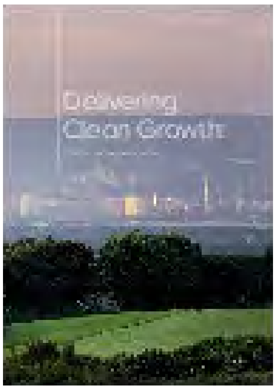
In this report, the Taskforce proposes a range of measures and actions to inform a new approach to CCUS deployment that will enable cost reductions to be secured. The study demonstrates that CCUS can deliver decarbonisation across industry, power, and provide solutions for heat and transport, by focusing on building a long term, commercially sustainable and cost-effective decarbonisation service industry for the UK. This may offer new industrial opportunities, secure long term jobs, deliver new economic development across industrial heartlands and secure international competitiveness through new decarbonised products and services.

The Taskforce identified several large industrial clusters in the UK as candidates for the development of CO_2 infrastructure and networks for capturing CO_2 and transporting it offshore in the North Sea and East Irish Sea for long term storage. The set of clusters include Teesside, Merseyside, Humberside, Scotland, and South Wales. However, the Task Force was not proposing specific projects; rather the UK government is committed to work with projects as they come forward in these clusters.

Among the conclusions of the study:

- Cost-effective CCUS can be achieved through industry and Government working together to:
    - Unlock early investment

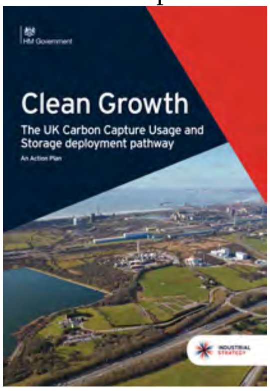
- Develop business models for CO_2 transport and storage infrastructure:
- Create CCUS clusters



UK Govternment Clean Growth. The UK Carbon Capture Usage and Storage deployment pathway. An Action Plan

This document highlighted the potential of clusters and committed to

- Report on the scope of the opportunity for maximising economies of scale by sharing T&S infrastructure and storage
- Set out and consult on a business model for transport and infrastructure in 2019.



4. Discussion – progress of hubs and clusters in relation to target

By the end of 2018 the world captured and stored approximately 35 Mt CO_2, the majority for EOR purposes. The cumulative injection was estimated to more than 230 Mt CO_2. The injection rate increased from the previuos year by around 1 Mt CO_2/year, represented by one -1 - project that came on line in 2018 (CNCP Jilin, China).

To reach the storage target by 2025, there is need for a10-fold increase in annual storage capacity the next six years. The Gorgon, Australia, and Alberta CO_2 Trunk line (ACTL) were delayed but may add 6 Mt CO_2/y in 2019. Only two other capture and storage facilities are in construction, both in China, adding a total capacity 1+ Mt CO_2/y. Even projects in advanced or early development will not add sufficient capacity by 2025, only 35 -40 Mt CO_2/y. These projects include the hubs and infrastructure projects described above.

All numbers from the Global Status of CCS, 2018 (GCCSI, 2018).

5. Conclusion and recommendations

The statement "CCUS infrastructure is key to unlocking huge clean growth potential in the UK and can contribute to a cost-effective pathway for reducing UK CO_2 emissions" (UK CCUS Cost Challenge Taskforce Report July 2018) seems to be supported by documents and projects reviewed above. However, despite all plans and studies it is noted that:

1. Only an offshore CCUS network has come online the last 15 years, no onshore infrastructure/network projects
2. Only one CCUS network is in construction, with anticipated start up in 2019, increasing capacity by 6 Mt CO_2/y
3. No project passed the Final Investment Decision (FID) gate in 2018
4. Projects in advanced or early development will only add 35 -40 Mt CO_2/y by 2025, at best.

The conclusion is clear: Progress on infrastructure development is lacking far behind what is necessary to reach the storage target. Strong action is required.

Recommendation 1:
- The Task Force continues to monitor the development of networks for CCUS, including clusters, hubs and infrastructure.
- The task Force updates this note on an annual basis (no need for an extensive Task Force report)

Recommendation 2:
CCUS networks are important to reach the target. To this end, decision makers from in industry and governments should work together to
- Bring infrastructure projects in advanced stage of development (FEED) to investment decision (FID)
- Develop and implement business models
- Accelerate planning of other infrastructure projects

Workshops in cooperation with GCCSI, IEAGHG, International CCS Knowledge Centre, CO2GeoNet, MI, others could be a contribution to this.

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CARBON SEQUESTRATION LEADERSHIP FORUM

TECHNICAL GROUP

Ad hoc Committee on

Monitoring Progress of the Technical Roadmap 2017

Results and Recommendations from "Phase 0"

April 2019

This note is a follow-up of the discussions in the CSLF Technical Group that were initiated in Venice in April 2018, and followed up in Melbourne in October 2018. It is based on discussions in the *ad hoc* group and a note from Norway 07 December 2018.

According to the CSLF Technical Group (from the Follow-up plans of the 2017 TRM) the technical Group has an obligation to monitor progress on target and recommendatins:

- Through its Projects Interaction and Review Team (PIRT), the CSLF should
  - Monitor the progress in CCS in relation to the Recommended Priority Actions.
  - Report the findings at Ministerial meetings.
  - Suggest adjustments and updates of the TRM.

In a teleconference of the *ad hoc* group 22 January 2019 it was decided to start the monitoring work by having group members rank the progress of five technical priority recommendations in the 2017 TRM using a traffic light approach. This will give indications of the efforts required and secure some results for the April TG meeting. The more extensive approach can then be presented to the whole group for discussions.

1. Target

Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) CO_2 per year by 2025 (or have permanently captured and stored of 1,800 Mt CO_2).

The Priority Recommendations are:

1. Infrastructure, hubs and clusters
Facilitate CCS infrastructure development.

2. Large scale projects

Leverage existing large-scale projects to promote knowledge-exchange opportunities.

3. RD&D

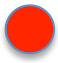
Drive costs down along the whole CCS chain through RD&D

4. Business models

Facilitate innovative business models for CCS projects.

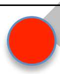
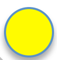
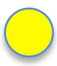
Results - Summary table

Progress towards target

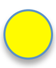
Target	Rating	Conclusion
Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) CO_2 per year by 2025 (or have permanently captured and stored of 1,800 Mt CO_2).		Need 10-fold increase in annual storage capacity next six years. Only one plant came online in 2018 (CNCP Jilin, China), increasing capacity by 1 Mt CO_2/y to 38 Mt CO_2/y. Projects in construction may add 7+ Mt CO_2/y in 2019. Projects in advanced or early development will not add sufficient capacity by 2025, only 35 -40 Mt CO_2/y.

Progress of priority recommendations (strategic actions) necessary to reach target.

Each action is in itself not sufficient but in practice necessary, or at least a strong enabler, for the target to be reached. Thus the target may still be red even though none of the priority recommendations are. There are other recommendations that also need to be met. The table below indicates where the strongest efforts from the Technical group are needed.

Priority Recommendation (Strategic Action)	Rating	Conclusion
1. Facilitate CCS infrastructure development.		Many good plans and studies but no infrastructure/network projects on line the last years; no project passed the Final Investment Decision (FID) gate in 2018
2. Leverage existing large-scale projects		Active leveraging through CSLF meetings, International Knowledge-Sharing Center , conferences, and reports. Not known which projects have used experience/knowledge from other projects.
3. Drive costs down along the whole CCS chain through RD&D.		Much good research going on that progress CCUS technologies but no break-through technologies reported or identified that at TRL 6 or higher have convincing evidence of significant cost reductions
4. Facilitate innovative business models for CCS projects		Many good plans and studies but progress on development of business models have not been implemented, in many cases due to lack of policy and regulatory environment relevant for CCUS projects.

 **Good, the progress contributes to reaching the Target**

 **Room for improvement, progress registered but insufficient to reach target unless new actions are initiated**

 **Poor progress, target will not be reached. Strong actions required**

ANNEX

Target

- **Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) CO_2 per year by 2025 (or have permanently captured and stored of 1,800 Mt CO_2).**

Increase in storage capacity last year:
~ 1 Mt CO_2/year

Number of projects that came on line last year:
One – 1.

Conclusion
Need 10-fold increase in annual storage capacity next six years. Only one plant came online in 2018 (CNCP Jilin, China), increasing capacity by 1 Mt CO_2/y to 38 Mt CO_2/y. Gorgon and ACTL are delayed but may add 6 Mt CO_2/y in 2019. Only two other are in construction, both in China, total capacity 1+ Mt CO_2/y. Even projects in advanced or early development will not add sufficient capacity by 2025, only 35 -40 Mt CO_2/y.

Recommended actions to speed up:
Increased efforts to get projects into planning, incentives must be put in place. International cooperation required

Sources:
GCCSI
The Global Status of CCS, 2017
The Global Status of CCS, 2018

Reported by:
Lars Ingolf Eide

PRIORITY ACTION/STRATEGIC ACTIONS

1. Infrastructure, hubs and clusters

- **Facilitate CCS infrastructure development.**

Infrastructure projects, operational or in construction, at end writing TRM 2017:

- **Operational:** Three - 3
  - **Name:** The Denver City (from 1985), Gulf Coast (from 1999), and Rocky Mountain hubs **(**from 1986**)**
  - **CO_2 sources:** Natural CO2 deposits; natural gas cleaning; hydrogen production from natural gas
  - **Transportation means:** Trunk-lines with feeder lines
  - **Storage sites:** Oil fields
  - **Business model:** EOR

- **In construction:** One - 1
  - **Name:** Alberta CO_2 Trunk Line
  - **CO_2 sources:** Fertilizer plant; bitumen refinery
  - **Transportation means:** Trunk-line with feeder lines
  - **Storage sites:** Oil fields
  - **Business model:** EOR

- **Infrastructure projects added in reporting period (2018):**
  - **Operational:** 0
  - **In construction:** 0
  - **Final Investment Decision (FID):** 0

- **Expected contribution from infrastructure projects to the target**
  - The one infrastructure project in construction (ACTL) may add a capacity of 2 Mt CO_2/year
  - Projects in advanced or early development are unlikely to amore than 35 -40 Mt CO_2/y by 2025.

- **General progress on other projects:**
  - One project in Norway received funds for FEED, aiming at FID in 2020
  - Two projects received funding from EU as Projects of Common Interest (PCI):
    - Port of Rotterdam, Netherlands
    - CO_2Sapling (UK lead European project)

- **Other progress:**
  - Increased focus on importance of clusters, hubs and infrastructure in Europe (EU Set-plan with CO_2 transport systems as PCI; projects like Teesside, HyNet, Align, H21 North of England, Humberside, Merseyside, Scotland, South Wales), Australia CarboNet, Southwest Hub), USA (workshop report on siting and regulation CCUS infrastructure), Korea (infrastructure into CCS Master Action Plan), IEAGHG (report addressing business models for infrastructure**),** numerous reports in the UK.

Conclusions

Progress on infrastructure development is lacking far behind what is necessary to reach the storage target. Strong action is required.

Despite many good plans and studies the conclusion is justified by:

1. No infrastructure/network projects have come on line the last years
2. Only one is in construction, with anticipated start up in 2019, increasing capacity by 6 Mt CO_2/y
3. No project passed the Final Investment Decision (FID) gate in 2018
4. Projects in advanced or early development will only add 35 -40 Mt CO_2/y by 2025, at best.

When seen in light of a statement by the UK CCUS Cost Challenge Taskforce Report July 2018: "CCUS infrastructure is key to unlocking huge clean growth potential in the UK and can contribute to a cost-effective pathway for reducing UK CO_2 emissions" it is clear that progress must be accelerated.

Identified common bottlenecks:
Commitment and funding beyond studies, lack of business models

Corrective actions, if any, by CSLF to speed development and implementation of infrastructure projects

- **Make decision makers**
  - Aware of the importance of hubs and infrastructure
  - Allocate funds for investments (beyond studies and plans)
  - Co-operate across businesses and nations

  Workshops in cooperation with GCCSI, IEAGHG, International CCS Knowledge Centre, CO2GeoNet, MI, others could be a contribution to this

Sources include:

- Norwegian State Budget 2019 (continued support to Norwegian Full-Scale Project
- European Commission SET-PLAN TWG9 CCS and CCU Implementation Plan (PCIs)
- Carbon Capture Journal Jan 27, 2019 (Port of Rotterdam and CO_2Sapling funded as PCIs))
- Presentations at CSLF TG meeting Melbourne Oct 2018 (Southwest Hub, CarboNet)
- Delivering Clean Growth: UK CCUS Challenge Task Force (UK clusters)
- Element Energy: Deployment of an industrial CCS cluster in Europe: A funding pathway
- IEAGHG Technical Report 2015-03 (Clusters).
- IEAGHG Technical report 2018-01 (Business models for infrastructure)
- Reports to UK BEIS by Pale Blue Dot and Element Energy in 2018
- UK Government (2018). Clean Growth. The UKCarbon Capture Usage and Storage deployment pathway. An Action Plan. https://www.gov.uk/government/publications/the-uk-carbon-capture-usage-and-storage-ccus-deployment-pathway-an-action-plan (Accessed 15 march 2019)
- Align CCUS Project, website and webinar Feb. 2019
- Presentations of H21 North of England by Northern Gas and Equinor (Brussels and Edinburgh Nov. 2019)
- The Global Status of CCS, 2017
- The Global Status of CCS, 2018

Impact on TRM:
Depends on development towards next version

Reported by:
CSLF Technical Group

2. Large scale projects

- **Leverage existing large-scale projects to promote knowledge-exchange opportunities.**

Actions during reporting period to leverage knowledge and experience from large scale projects

- The CSLF Technical Group is active in leveraging knowledge and experience from large-scale projects. From the past 5 years alone, CSLF Technical Group meetings or workshops have included the following activities to leverage knowledge and experience from large-scale projects:
    - April 2019 TG Meeting: Presentations from Project Tundra, ADM; Additionally, CSLF members are invited to attend the MGSC Annual Meeting, which includes discussion of the ADM project, including other activities such as CarbonSAFE projects in the region.
    - October 2018 CSLF Meeting in Melbourne, Australia: Gorgon, CarbonNET, Southwest Hub. Policy meeting also included an update on the Hydrogen Energy Supply Chain Project between Australia and Japan.
    - April 2018 CSLF Meeting in Venice, Italy: Update on MHI's CDR process and commercial experience; Update on Fort Nelson Project; Norcem Carbon Capture Project
    - December 2017 meeting in Abu Dhabi, UAE: Update on ROAD Project, Uthmaniyah project, Emirates Steel Project
    - May 2017 CSLF meeting in Abu Dhabi, UAE: Emirates Steel Project, Uthmaniyah, ADM; Workshop in conjunction with that meeting: Emirates Steel, Shell Quest, Petra Nova, Boundary Dam; SABIC; Discussion of Full-scale CCUS activities in Norway.
    - October 2016 in Tokyo, Japan: More focused on large pilot/demo projects such as Tomakamai and NetPower
    - June 2016 meeting in London, UK: Policy Group – International Collaboration on Large-scale Saline injection; Bellona – CO2 Market Makers for Strategic EU Hubs and Clusters
    - November 2015 meeting in Riyadh, KSA: SABIC; Ministerial Meeting – Panel on large-scale CCUS projects: ADM, ROAD, Uthmaniyah, Occidental Petroleum's CO2-EOR business case.
    - June 2015 meeting in Regina, Saskatchewan: Workshop on Lessons Learned from Large-scale projects: Presentations were from ROAD, ADM, Kemper, Quest; PCOR Bell Creek Project; Equinor (Statoil at that time); Boundary Dam (SaskPower); Dakota Gasification
    - Highlight workshops from CSLF that had large-scale project engagement
- In addition to the CSLF, there are numerous other activities that focus on leveraging knowledge and experience from large-scale CCUS projects.
    - International Knowledge-Sharing Center (SaskPower/Canada). Their entire mission is to support new global CCS projects with business development, operations, and technological improvements to advance the deployment of CCS facilities around the world.
    - CLIMIT Summit: Includes significant number or presentations on Norwegian projects such as Sleipner, Snohvit, and the full-scale CCS projects. Also includes broader global participation, which touches upon large-scale projects.
    - IEAGHG/GHGT Conferences. The GHGT-14 conference in Melbourne, Australia included the following sessions: Session 1C: Large-scale Integrated Projects Experience; Session 2C: Regional Projects (this session included Boundary Dam and also a previous US project: AEP's Mountaineer Power Plant – Stratigraphic Test Well to Site Closure)' Session 5C: Panel Discussion 3: From Projects to Infinity: Large-scale project experiences to be shared; Session 6C: Panel discussion 4: The status and potential of the Norwegian-

EU CCS Project; There were also numerous other sessions that included results from large-scale projects, some very technical.
  - DOE's RCSPs typically conduct annual meetings which are open to the public or research community. For example, MGSC Annual Meeting: http://sequestration.org/resources/reports.html.
  - CO2GeoNet: The 13th Open Forum included presentations from several large-scale projects that captured lessons learned or described techniques used in their storage projects. It also included a post-Open Forum workshop that brought together Norwegian and American experts to discuss a number of topics on large-scale CCUS applications. Additionally, the 12th and 11th Open Forums also included additional presentations, panels, and workshops on knowledge sharing from large-scale or integrated projects. For example, the 11th Open Forum included a workshop focused on dealing with liability: final closure, liability and transfer of responsibility of the storage site.
  - DOE's Annual CCUS Meetings have included updates on large-scale CCUS projects:
- Reports (Peterhead/Goldeneye, Boundary Dam, Air Products, Sleipner, In Salah)
  - Peterhead/Goldeneye: GHGT-13 included a paper on experience in developing the Goldeneye Storage Permit Application. There is also a paper published on the Summary Report for the Full CCS Chain for the Peterhead project: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/531394/11.133_-_FEED_Summary_Report_for_Full_CCS_Chain.pdf
  - Boundary Dam: IEAGHG report: https://ieaghg.org/docs/General_Docs/Reports/2015-06.pdf
  - Air Products project: IEAGHG Report: http://documents.ieaghg.org/index.php/s/YKm6B7zikUpPgGA?path=%2F2018%2FTechnical%20Reports
  - Equinor and partners have provided/shared information from the Sleipner and Snohvit projects. For example, Equinor has made datasets available via the IEAGHG: https://ieaghg.org/terms-of-use?id=248:sleipner-benchmark-model
  - In Salah Project: There is significant information available on this project as well. Has been presented on numerous occasions: https://www.spe-uk.org/aberdeen/knowledgefiles/In%20Salah%20Gas%20CO2%20Project%20Overview%20SPE%20June%202013pdf.pdf; http://www.cgseurope.net/UserFiles/file/Ankara%20workshop_june%202012/presentations/Allan%20Matheison.pdf
  - Weyburn-Midale, extensive number of publications and literature on this project: https://ptrc.ca/projects/weyburn-midale
  - IEAGHG and GCCSI: Numerous reports from both organizations that leverage key learnings from large-scale projects. Additionally, some of their reports are also further reaching and can influence decisions on new large-scale projects such as finance and regulatory aspects.
  - DOE Best Practice Manuals: https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/best-practices-manuals
- Other workshops/meetings:
  - TCM and SINTEF workshop: http://www.tcmda.com/en/Press-center/News/2016/TCM-shares-crucial-CCS-lessons-learned-with-Road/
  - 1st, 2nd, and 3rd workshops on offshore carbon storage
  - IEAGHG network meetings include numerous lessons learned from large-scale projects.
  - IEAGHG conferences other than GHGT series, such as Post-Combustion Carbon Capture Conference.
  - Numerous others, have not captured a fully comprehensive list.

Projects that have used the experience:

  - It is unknown which projects, i.e., those being proposed now or previously, have used experience/knowledge from other projects. It may also be difficult to track this particular information.

Conclusion
Numerous examples of active leveraging through CSLF meetings, International Knowledge-Sharing Center , conferences, and reports.

Identified bottlenecks for knowledge exchange:
No significant bottlenecks, but intellectually properties around capture technologies, detailed cost breakdown and negative experiences

Corrective actions, if any, by CSLF to facilitate exchange of experiences between large scale projects
No corrective actions required but CSLF should continue to engage large-scale projects and facilitate information and knowledge-sharing..

Sources:
Sources for the information include the CSLF and its Technical Group members; CO2GeoNet website; U.S. Department of Energy and National Energy Technology laboratory websites, Other sites referenced in the body of the report.

Impact on TRM: Measures progress in this area.
Reported by: CSLF Technical Group

Template reporting progress, Phase 0

3. RD&D

- **Drive costs down along the whole CCS chain through RD&D**

RD&D achievements/status/progress in relation to specific technical recommendations of TRM (Annex B).

General
Progress is being made (e.g. papers presented at GHGT14). Globally, significant R&D investments are occurring (Respondents to CSLF Maximization and Knowledge Sharing survey mostly indicated stable RD&D budgets for CCUS; many national and regional programmes). There is good progress and sustained efforts at the lab- and bench-scale.

Mission Innovation CCUS Challenge holds promise of concerted international efforts, increased bi- or multilateral co-operations in CCUS RD&D emerging.

Examples of international cooperation at the regional are the cooperative programmes the European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL) and Accelerating CCS Technologies (ACT). ECCSEL is a permanent pan-European distributed research infrastructure, ERIC (European Research Infrastructure Consortium). Within the initial 5 European founding Member countries (France, Italy, the Netherlands, UK and Norway (Operations Centre)), 15 service providers offer open access to more than 55 world class CCS research facilities across Europe. The whole CCS chain is included.

ACT is an international initiative to facilitate RD&D and innovation within CO_2 capture, utilisation and storage (CCUS). Ten European countries and USA, who joined ACT in 2018, are working together in ACT with the ambition to fund world class RD&D innovation that can lead to safe and cost effective CCUS technology.
The ambition of ACT is to facilitate the emergence of CCUS via transnational funding aimed at accelerating and maturing CCUS technology through targeted innovation and research activities.

Capture
Globally, there are many test facilities for smaller scale capture pilots that have been in operation for many years, and several capture technologies have moved from small pilots to large pilots. This has partly been due to cooperation between test facilities with encouraging results. The National Carbon Capture Centre (NCCC) in USA and the Technology Centre Mongstad (TCM) in Norway, where particularly mentioned by respondents to the CSLF Maximization and Knowledge Sharing survey. The International Test Centre Network (ITCN) is an important factor in bringing capture technologies up the TRL ladder.

Respondents to the CSLF Maximization and Knowledge Sharing survey indicated particular progress in modular design of capture systems and Pd membranes. One respondent indicated that an extremely cost effective capture technology had been developed but gave no further evidence or reference.

Storage
For pilot-scale projects and field tests, storage lags behind capture. However, respondents to the CSLF Maximization and Knowledge Sharing survey said that valuable experience and knowledge have been gained for RD&D projects, Otway and Tomakomai were particularly mentioned. Progress on fiber optic sensing for monitoring storage sites was also reported.

For storage, it is probably somewhat more challenging to identify progress than for capture, due to challenges like the level of characterization required and the acquisition of CO_2 for injection.

Utilisation
Much work is reported in the literature, but appears to be related to applications rather than technologies as such.

In the CSLF Maximization and Knowledge Sharing survey the majority of respondents (10 of 16) indicated incentives are being used for Utilization technologies

Conclusion
Much good research going on that progress CCUS technologies but no break-through technologies reported or identified that at TRL 6 or higher have convincing evidence of significant cost reductions

Identified bottelnecks for RD&D:

Corrective actions, if any, by CSLF to facilitate exchange of RD&D results

Need sustained, continued R&D investment beyond the lab- and bench-scale. Need to start moving promising technologies to the pilot-scale. Also, incremental advancements from R&D are important and should be considered for investment along with transformative technologies. While there has been good progress on CO2 injection pilots, need to re-visit what has been learned and focus of the next set of pilot projects.

Sources:

Impact on TRM:
Depends on development towards next version.

Reported by:
CSLF Technical Group

4. Business models

- **Facilitate innovative business models for CCS projects**

Summary of business models implemented or suggested business models during reporting period.

Business models implemented:
EOR has been a market driver for decades in the United States

The US, the 45Q tax credit (E.G. **https://www.catf.us/wp-content/uploads/2017/12/CATF_FactSheet_45QCarbonCaptureIncentives.pdf**) and low-carbon and renewable fuel standards, which also place a value on carbon have the potential to spur investment.

Other progress:
Business models exist to varying degrees in different regions. For example, public-private models are under consideration/development in, amongst others, Norway and UK.

IEAGHG, IPIECA, Pale Blue Dot, Pöyry/Teesside Collective and UK BEIS reports/presentations on topic. Heightened awareness of importance. Globally, other efforts, whether incentives, taxes or direct government investment, have been utilized or considered.

Increasing focus on utilisation of CO_2 as part of a business concept for CCUS.

An ACT event**:** Framework for CCS risk sharing and business model selection, workshop in Brussles Wednesday, March 13-15, 2019. The aim of the workshop will be to present and discuss the methodology developed to understand the main components of a CCS business model and a business case at system and sector level (**http://www.act-ccs.eu/events/2019/3/13/framework-for-ccs-risk-sharing-and-business-model-selection**).

In the CSLF Maximization and Knowledge Sharing survey ~50% indicated CCS incentives have been used to implement CCS since January 2018, including:
- In USA, the 45Q Tax credit, the renewable fuel standard and the low-carbon fuel standard
- In Australia, ANLEC R&D has developed a portfolio of research shaped by the priorities for reducing investment risk for these three proponents.
- In the United Kingdom, government funded studies that include business models
- In Norway, a business model for the full-scale project has been outlined.

Many conferences and workshops on CCUS include sessions on business models or related topics (e.g.. GHT14 2018; CLIMIT SUMMIT 2019).

Conclusions

Despite many good plans and studies the conclusion on the development and implementation of business models for CCUS is:

Progress on development of bussiness models have not been implemented, perhaps due to lack of policy and regulatory environment relevant for CCUS projects. Progress is behind what is necessary to support the development of CO_2 hubs, clusters and infrastructure, which will be needed to reach the storage target. Action is required.

Identified common bottlenecks:

Commitment and funding beyond studies for projects on the drawing board.

Corrective actions, if any, by CSLF to facilitate innovative business models

Business models must be in place before infrastructure projects will make an investment decision. There is a need in many cases to develop guidance or rules for actual implementation so project developers and financiers have the ability to make sound investment decisions. Need to ensure a sound technological and scientific basis is available to ensure appropriate business models are developed. Models need to be tailored to specific regions/countries to meet their needs/market conditions**.**

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Impact on TRM
Depends on development towards next version

Reported by:
CSLF Technical Group

Carbon Sequestration Leadership Forum

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MESSAGE FROM CSLF TECHNICAL GROUP TO CEM AND CSLF MINISTERS

Distinguished Ministers:

At the CSLF's 7th Ministerial Meeting, in Abu Dhabi in 2017, the CSLF Technical Group published a new edition of the **CSLF Technology Roadmap**. The clear message to Ministers is that **Governments have a critical role in accelerating the deployment of carbon capture, utilization and storage (CCUS)**. Widespread deployment of CCUS is a necessity for the Paris Agreement goal of limiting global temperature increase to 2°C to be achieved. The Roadmap recommends that the CSLF adopt the following targets for CCUS:

2025: Permanent storage of at least 400 megatonnes (Mt) CO_2 per year (or have permanently captured and stored 1,800 Mt CO_2)
2035: Permanent storage of at least 2,400 Mt CO_2 per year (or permanent capture and storage of in total 16,000 Mt CO_2)

The Roadmap provided priority recommendations to achieve these goals:

- **Facilitate CCUS infrastructure development.** Coping with the large volumes of CO_2 from power plants and industrial clusters will require CO_2 infrastructure and networks that include capture from sources, transport, and storage. Shared infrastructures have the potential to drive down costs and lower barriers for CCUS projects.
- **Leverage existing large-scale projects for knowledge-exchange opportunities.** The first large-scale CCUS facilities have indicated that significant cost reductions can be achieved for the next facilities. Knowledge transfer can give important input to achieve reduced capital and operational expenditures and to provide increased confidence for deployment.
- **Drive down costs along the whole CCUS chain through research, development and demonstrations (RD&D).** CCUS technologies are continuously in development, both with regard to improvements of currently available commercial technologies as well as novel or emerging technologies. The aim of the RD&D is to find affordable solutions.
- **Facilitate innovative business models for CCUS projects.** The development of infrastructure and networks is closely linked to the split of risks and costs between the stakeholders, including private enterprises and governments.

In addition, the Roadmap provides more detailed recommendations on technology developments that are required for CCUS for it to make a contribution in reaching targets.

The CSLF has evaluated progress since 2017 for the four technical priority recommendations:

<u>Good Progress</u>:

- **"Leveraging existing large-scale projects to promote knowledge-exchange opportunities"** has been successful. Existing projects have shown a willingness to share lessons learned at CSLF Technical Group meetings and workshops and by information exchange through allied organizations such as the IEAGHG, GCCSI, and CO_2GeoNet. There has also been a significant amount of activity at the national and sub-national level. New developers should be further encouraged to learn from existing large-scale projects.

Challenges Remain:

- The action **"facilitating CCUS infrastructure development"** has shown poor progress regarding real investments despite several good studies. Commercial projects include networks of CO_2 pipelines onshore in the United States and a smaller one offshore Brazil, primarily for utilizing CO_2 for enhanced oil recovery (EOR). One onshore network is scheduled to come online in Canada in 2019. However, stronger actions are needed if the overall target is to be achieved.
- For the strategic action **"driving down costs through RD&D"**, some progress has been made but not enough to reach the overall target. Significant research and development (R&D) investments are occurring globally and there is good progress and sustained efforts at the lab- and bench-scale. There is also increasing collaboration internationally. However, the challenge is on scaling up technologies.
- For the strategic action **"facilitating innovative business models"**, there are various public-private models under consideration/development but there is a need in many cases to develop guidance or rules for sound decisions regarding CCUS. Much will be dependent upon local and regional market conditions.

The evaluation also considered progress towards the CO_2 storage target, which depends on six other non-technical CSLF recommendations. **The CSLF concludes that insufficient progress is being made for achieving the Roadmap's 2025 target and that increased efforts are needed to achieve the 2035 target.**

The CSLF's Recommendations

The CEM Ministers should:

- **Foster a predictable business environment for development of large-scale CCUS projects.** This could include policy and financial incentives, a practical regulatory environment, cost- or risk-sharing for early stage demonstration or commercial-scale projects, and stimulating cross-business and cross-border cooperation.
- **Facilitate (e.g., through co-funding) cross-industry projects** to ensure lowest total cost for the combined capture, transportation, utilization and/or storage infrastructure and networks.
- **Continue to promote RD&D investments in CCUS to drive down costs**:
  - Continue to fund early stage R&D and encourage transformative technologies as well as incremental advancement to progress technologies to the pilot-scale.
  - Support continued RD&D efforts that promote commercial deployment and business opportunities for more advanced carbon utilization, in particular for early-stage technologies. Lifecycle analyses should continue to ensure that technologies result in net greenhouse gas emissions reductions.
  - Continue to promote global RD&D collaboration that leverages knowledge, capabilities, facilities and funding that further drives down costs and increases the availability of CCUS as a greenhouse gas mitigation option around the world.
- **Continue to promote knowledge-sharing from large-scale projects**. This is important in framing continued RD&D and informing the development and refinement of business models for CCUS deployment.

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MEETING SUMMARY

Projects Interaction and Review Team (PIRT) Meeting
Warrnambool, Victoria, Australia
16 October 2018

Prepared by the CSLF Secretariat

LIST OF ATTENDEES

PIRT Active Members

Australia:	Andrew Barrett (*Chair*), Max Watson
Canada:	Mike Monea
France:	Didier Bonijoly
Japan:	Ryozo Tanaka, Jiro Tanaka
Norway:	Lars Ingolf Eide, Åse Slagtern (*Technical Group Chair*), Espen Bernhard Kjærgård
Saudi Arabia:	Pieter Smeets
United Kingdom:	Brian Allison
United States:	Mark Ackiewicz, Sallie Greenberg

Allied Organizations

IEAGHG:	Tim Dixon

CSLF Secretariat Richard Lynch

Invited Speaker

Max Watson, Business Strategy Manager, CO2CRC, Australia

Observers

Australia:	Chamaka de Silva (*Department of Industry, Innovation and Science*) Fiona Koelmeyer (*CO2CRC*) Kingsley Omosigho (*Department of Industry, Innovation and Science*) Abdul Qader (*CO2CRC*)
Norway:	Eva Halland (*Norwegian Petroleum Directorate*) Stig Svenningsen (*Ministry of Petroleum and Energy*) *
United States:	Jarad Daniels (*Department of Energy*) * Katherine Romanak (*University of Texas*) Adam Wong (*Department of Energy*)

* Policy Group delegate

NOTE: The PIRT is a standing committee of the CSLF Technical Group and, as such, is not comprised of full Technical Group membership. This PIRT meeting was held in Warrnambool because of a site visit to the nearby CO2CRC Otway Research Facility, which occurred immediately following the meeting.

1. **Welcome**

Outgoing PIRT Chairman Andrew Barrett welcomed participants to the 29th meeting of the PIRT by acknowledging and paying respect to the traditional custodians of the land and to their Elders; past, present and future. Mr. Barrett also thanked the meeting organizers from CO2CRC and the Department of Industry, Innovation and Science, and stated that there would not be any new project up for CSLF recognition during this meeting; the two major items on the meeting agenda were an update from the CSLF-recognized CO2CRC Otway Project and a presentation from the Technical Group's ad hoc committee for task force maximization and knowledge sharing.

2. **Introduction of Meeting Attendees**

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

3. **Adoption of Agenda**

The draft agenda for the meeting, which had been prepared by the CSLF Secretariat, was adopted without change.

4. **Approval of Meeting Summary from Venice PIRT Meeting**

The Meeting Summary from the April 2018 PIRT meeting in Venice was approved as final with no changes.

5. **Report from CSLF Secretariat**

Richard Lynch provided a two-part report from the Secretariat, which covered the status of CSLF-recognized projects and outcomes from the previous PIRT meeting.

Concerning the portfolio of CSLF-recognized projects, Mr. Lynch stated that as of August 2018 there were 32 active projects and 22 completed projects spread out over five continents.

Mr. Lynch reported that there were two outcomes from the Venice meeting:

- The PIRT recommended approval by the Technical Group for the Enabling Onshore CO_2 Storage in Europe (ENOS) Project to be a CSLF-recognized project. The Technical Group, at its meeting in Venice, also approved the project and final approval by the Policy Group would happen at its upcoming meeting on October 18th.
- There was consensus that measuring progress on recommendations from the 2017 CSLF Technology Roadmap (TRM) is one of the PIRT's most important areas of interest.

Mr. Lynch concluded his report by stating that there were two Action Items from the previous PIRT meeting:

- The Secretariat would set up an offline discussion for PIRT delegates to develop details for moving forward on finding ways to measure progress on TRM recommendations. (*Note: This was superseded by a Technical Group outcome at its meeting the next day*.)
- The Secretariat will produce summaries of questions or comments about projects being reviewed by the PIRT for CSLF recognition. These summaries would be made available prior to the PIRT meetings where the projects are to be reviewed.

6. Report from the Ad Hoc Committee for Task Force Maximization and Knowledge Sharing

Committee Chair Sallie Greenberg made a presentation that followed up on the April 2018 Technical Group meeting. During that meeting there was consensus of a need to measure progress on technical recommendations from the 2017 TRM and also to assess the impact and usage of task force reports. Dr. Greenberg reported that, following the Venice meeting, a small ad hoc group came together for this purpose and during the middle of 2018 conducted a survey to gather details on how TRM and task force reports were being used. In all there were 21 respondents representing ten CSLF member countries; thirteen of the responses were from delegates, 4 from observers, and 4 from people who did not identify their specific roles. Additionally, 12 of the respondents had participated in Clean Energy Ministerial (CEM) activities, 14 in Mission Innovation activities, and 7 in Europe's Accelerating CCS Technologies (ACT) initiative.

Concerning TRM usage, Dr. Greenberg reported that the majority of respondents have used it in formation of national RD&D CCS strategies. Examples of this include planning new CCUS strategies in China, setting a global context for Norway's national discussions about policy and RD&D priorities for CCS, informing the CCS development direction in Canada, and playing a role in a forthcoming National Petroleum Council report and recommendations to the United States Department of Energy. However, Dr. Greenberg also reported one respondent to the survey wrote that, despite the usefulness of the TRM, the document was little-known outside the CSLF and its member countries.

There was also useful information from the survey about usage of task force reports. The most widely-used reports are those which focus on CO_2 capture technologies, hydrogen with CCS, offshore CO_2 storage, and CO_2 utilization through enhanced oil recovery (EOR). These reports have been most often used for knowledge and technical gain, RD&D program planning, and (by the ISO TC265 committee) in developing standards. Additional usages have been for technology assessment, strategic planning, and proposal development. Dr. Greenberg stated that more than half of the respondents revealed that task force reports have been utilized in decision making, policy making, or knowledge sharing forums. As for being referenced in non-CSLF reports, the most frequently cited task force reports focus on offshore CO_2-EOR, CO_2 capture, and offshore CO_2 storage. And as for overall perceived usefulness, the task force reports most often recommended to others were Practical Regulations and Permitting Process, Hydrogen Production and CCS, Offshore CO_2-EOR, and Bioenergy CCS.

Dr. Greenberg also provided additional data resulting from the survey:

- All but one of the respondents had viewed and/or downloaded the TRM.
- Five of the respondents reported at least one CCS infrastructure project, with seven reporting 2-4 CCS infrastructure projects.
- Approximately half of the respondents indicated that incentives have been used to implement CCS since January 2018, and approximately half of the respondents indicated that incentives for knowledge sharing from large-scale projects had occurred. Additionally, the majority of respondents (10 of 16 respondent countries) indicated that incentives are being used for CO_2 utilization technologies.
- Concerning RD&D budgets, there has been an increase for 2 of 16 countries covered by the survey, there has been a decrease for 4 of the 16 countries, and no significant increase or decrease for the other 10 countries.

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In concluding, Dr. Greenberg provided some suggestions for future Technical Group activities, based in part on information gleaned from the survey. It identified that there was an obvious need to track TRM technology recommendations, which will be an ongoing priority of the ad hoc committee, but beyond that the survey indicated there appear to be several areas where activities are warranted. These include:

- Hub/infrastructure;
- Support of developing countries (*note: this was approved by the CSLF's Capacity Building Task Force in its meeting the next day*);
- Cost-effective capture technologies;
- More clarity on economic benefits of low-carbon policy; and
- Providing technical inputs into any business model and socio-economic benefits discussions.

Dr. Greenberg provided that a future workshop on hub/infrastructure would be an especially worthwhile activity, especially if it resulted in a report as a deliverable. Also, better knowledge sharing of all Technical Group results is imperative, and the Technical Group should find better methods for wider distribution of its reports, especially the TRM.

In the ensuing discussion, Lars Ingolf Eide agreed that technical workshops are an important part of Technical Group activities, and stated that discussions are already underway with the IEAGHG about co-hosting a future workshop themed on hydrogen production with CCS. Such a workshop would result in an IEAGHG report. Mark Ackiewicz seconded the need for better ways of distributing Technical Group reports and other results. There was general agreement on this and consensus that (a) the Secretariat, on behalf of the PIRT, should write and send out brief informational emails concerning new Technical Group reports and other important results to the overall CSLF mailing list and that (b) the Technical Group's allied organizations should then also provide this information to the people on their own mailing lists. Jarad Daniels stated that the CSLF Policy Group would also take any key recommendations from the TRM and Technical Group task forces and convey this information to CSLF Ministers.

Concerning the future of the ad hoc committee, there was agreement that it should continue to obtain baseline data such as that presented by Dr. Greenberg while determining ways to track TRM recommendations and, in general, improve knowledge sharing. Several delegates recommended that the ad hoc committee continue its activities for at least another year, though that directive would have to come from the Technical Group as a whole.

Finally, concerning the TRM, there was discussion on what would be the proper timing for the next revision of the document. Mr. Eide suggested that the TRM is useful enough that it should be updated on a regular basis, perhaps on a 4-year cycle. Further discussion was tabled pending the next day's full Technical Group meeting.

7. Update on CSLF-Recognized Project: CO2CRC Otway Project

Max Watson, representing project sponsor CO2CRC, provided a progress report on the status and activities of the CO2CRC Otway Research Facility. Dr. Watson stated that the facility is one of the most comprehensive CO_2 storage demonstration laboratories in the world, and is verifying the fundamental science of CO_2 storage in Australia while further validating injection, storage and monitoring technologies globally. The facility features a state-of-the-art seismic monitoring array for observing and benchmarking subsurface technologies and processes, and has produced and made available high quality, comprehensive datasets from its previous operations.

Dr. Watson reported that the Otway Project, to date, has consisted of three stages. An initial stage, from 2004 to 2009, demonstrated safe transport, injection and storage of CO_2 into a depleted gas reservoir. The second stage, which started in 2009 and will conclude in 2019, has demonstrated safe injection of CO_2 into a saline formation and is performing well and reservoir characterization while also testing advanced monitoring and verification of storage technologies and investigating methods for CO_2 plume stabilization. The third stage, which began in 2015 and will conclude in 2022, is demonstrating safe, reliable and cost-effective technologies for subsurface monitoring of stored CO_2. Additional stages of the project are anticipated, one of which will improve the capability to predict the role of geologic faults in controlling CO_2 fluid flow in the near surface while improving near surface monitoring capabilities.

For the third stage of the project, Dr. Watson stated that there are four main types of activities that are in progress: developing high-resolution real-time monitoring capabilities for identifying and tracking CO_2 subsurface plume movement; employing non-invasive monitoring techniques which will be acceptable for community and regulators; evolving these technologies from benchtop application to in-field validation that is aligned with operator need; and providing a suite of technologies and workflows that can be selected to create solutions which optimize effectiveness and costs in commercial monitoring projects. Dr. Watson closed his presentation by describing some of the accomplishments of the Otway Research Facility. These include demonstrating real world CCS for both the local community and the community at large, providing an opportunity to overcome real-world engineering challenges under operational conditions, enabling a decrease in technical risk and uncertainty while testing technical performance prior to embarking on large-scale projects, and providing an impetus to regulators to confront some of the regulatory issues when there is a real project.

8. General Discussion and New Business

Katherine Romanak noted that her organization, the University of Texas's Bureau of Economic Geology, has hosted several CSLF-branded technical workshops in the past few years. For these, CSLF capacity building funds had been used to bring in representatives from CSLF members that are developing countries. However, the CSLF capacity building funds do not allow funding travel for representatives from non-member countries. For the first workshop, the United Nations Climate Technology Center and Network (CTCN) provided travel funds for representatives from non-CSLF countries but this was unfortunately not provided for subsequent workshops. Jarad Daniels responded that use of capacity building funds for this purpose is being revisited by the CSLF Capacity Building Governing Council, which was scheduled to meet on October 16th following the Technical Group meeting. Dr. Romanak also noted that the CSLF is a fabulous platform for engaging developing countries and that she would be mentioning that during her presentation at the following week's GHGT14 conference.

9. Adjourn

Chairman Andrew Barrett once again thanked the meeting organizers from CO2CRC and the Department of Industry, Innovation and Science for organizing the field trip and arranging for the site of the PIRT meeting. Prior to adjourning the meeting, Mr. Barrett stated that this would be his final meeting due to impending retirement and thanked the CSLF for the opportunity to be PIRT Chair over the past three years.

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Summary of Meeting Actions and Outcomes

- The CSLF Secretariat, on behalf of the PIRT, will write and send out brief informational emails concerning new Technical Group reports and other important results to the overall CSLF mailing list. Allied organizations should then also provide this information to the people on their own mailing lists.
- The ad hoc committee for task force maximization and knowledge sharing was advised to continue with no firm end date. The Technical Group will provide specific direction and purpose.

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PROJECTS INTERACTION AND REVIEW TEAM (PIRT)
Engagement of CSLF-recognized Projects
Background and Status

Background

At the London meeting in June 2016, there was consensus by the CSLF that the PIRT should find ways to improve its interactions with CSLF-recognized projects. To that end, a new format was developed for projects to inform the CSLF on their status:

Project Name:

Brief non-technical description:

Is the project still active?

If not, when did it end, and why?

If still active, what have been the important factors in its continued progress, and why?

Please briefly describe the overall project timeline (with emphasis on next six months):

What kinds of sharable information have been produced?

Please describe any interesting outcomes or gains in knowledge.

Who is the project's main point-of-contact for the CSLF?

A survey of projects was conducted prior to the CSLF's 2017 Mid-Year Meeting in Abu Dhabi, and a summary of preliminary results, based on a collection of reports received from 25 of the 35 active CSLF-recognized projects as well as one recently-completed project, was presented at that meeting.

Findings

Findings of general interest to other CSLF activities, including the Technology RoadMap (TRM):

1. The 'active' CSLF-recognized projects included many operative or soon-to-be-operative large-scale integrated CCS projects (LSIPs).
2. Success factors: Factors influencing success are, not surprisingly,
   a. Secure funding
   b. Encouragement from owners,
   c. Collaboration between stakeholders like industry, academia, authorities and research organisations
   d. Good communications with locals and other stakeholders
3. Factors leading to project stop:
   a. Target reached
   b. Lack of funding

None of the projects reported failure to meet targets as reason for stop.

Specific comments to the returned project forms:

1. Few of the returned project forms address general technology needs (we did not ask), only project specific challenges or next steps.
2. The questions were answered in a variety of ways with respect to completeness and quality of the returned forms.
    a. For example, the question of factors that secured continued progress was answered both in terms of financial support and moral encouragement, as well as in terms of technical achievements but often without indications of what mattered most.
    b. The question on information was answered both in very general terms and with specific references and links
3. Role of CSLF recognition: None of the project engagement forms address the overall CSLF goals, nor is there information on why CSLF recognition was sought, what the benefits, if any, have been, nor what the projected expected from CSLF. The reason is that this was not asked for. It may be up to PIRT to decide how the projects contribute to the CSLF goals, but it might have been useful to challenge the projects on this.
4. Fulfilment of criteria: Most projects satisfy at least one of the three criteria. However, there are a few where it is not obvious how they meet at least one of the criteria. These were probably recognized prior to the establishment of the criteria.
5. CO_2 captured/stored: This question is relevant for some but far from all projects. Some information on amounts of CO_2 captured and/or stored had to be taken from elsewhere and could not always give the accumulated amount to date. A direct question might have been useful.
6. Outcomes and advances: Described outcomes range from the obvious to very specific technical learnings.
7. Information: Access to information ranges from very open to confidential.

Recommended Actions

- Decide what, if anything, CSLF can offer to the projects.
- Decide what CSLF/PIRT wants to achieve by recognising projects.

Follow-Up Activities since the 2017 Meeting

The PIRT has not yet conducted a follow-up survey of the projects. (Note: The time frame for doing such a survey will need to be revised. There had been consensus to conduct surveys in years when there would be a CSLF Ministerial Meeting, but it now seems unlikely that there will be any more CSLF Ministerials.)

There was consensus during the 2017 Meeting that the survey format be revised to include the following information requests:

- Why did you seek CSLF recognition for the project?
- What benefits have there been (or are expected) from CSLF recognition?

Terms of Reference

Revised 03 December 2017

CSLF Projects Interaction and Review Team (PIRT)

Background

One of the main instruments to help the CSLF achieve its goals is through the recognition of projects. Learnings from CSLF-recognized projects are key elements to knowledge sharing which will ultimately assist in the acceleration of the deployment of carbon capture, utilization and storage (CCUS) 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 with 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 of recognized projects and identify synergies, complementarities and gaps, providing feedback to the Technical Group
- Recommend where it would be appropriate to have CSLF-recognized projects.
- Foster enhanced international collaboration for CSLF-recognized 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.
- Provide input for further revisions of the CSLF Technology Roadmap (TRM) and respond to the recommended priority actions identified in the TRM.

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.
- 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

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 PIRT. The PIRT has the responsibility of keeping the Project Submission Form updated in terms of information being requested from project sponsors.

Additionally:

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

Operation and Procedures of the PIRT

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

Project Recognition

- Completed Project Submission Forms shall 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 any project proposed for CSLF recognition.
- At PIRT meetings or via proxy through the PIRT Chair, individual country representatives will be required to comment on projects proposed for CSLF recognition.
- Recommendations of the PIRT should be reached by consensus with one vote per member country only.

Information Update and Workshops

- The PIRT shall define a process for interaction with CSLF-recognized projects which includes and describes benefits of project recognition to the project sponsor as well as the CSLF. Project engagement will be done by the PIRT every two years, or in years where there is a Ministerial Meeting; the PIRT will assist in ensuring information is sent to the Secretariat.
- The PIRT will assist in facilitating workshops based on technical themes and technical presentations in Technical Group meetings as required.
- As required, the PIRT will draw on external relevant CCUS expertise.

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) 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.

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.

Terms of Reference

Revised 5 December 2017

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 3.3 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 activities, and following reports from the Technical Group make recommendations on the direction of such projects and activities. A collaborative project or activity is one that results from cooperation between the CSLF and its stakeholders and/or sponsors of recognized projects (as per Section 4.1 below).
- 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 3.3 of the CSLF Charter, the Policy Group will:

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

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

1.2. Technical Group.

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

- Identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity.
- Identify potential areas of multilateral collaboration on carbon capture, transport and storage technologies.
- Foster collaborative research, development, and demonstration (RD&D) projects and activities reflecting Members' priorities.
- Assess regularly the progress of collaborative projects and activities, and make recommendations to the Policy Group on the direction of such projects and activities.
- 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 3.4 of the CSLF Charter, the Technical Group will:

- Recommend collaborative projects and activities to the Policy Group.
- Set up and keep procedures to review the progress of collaborative projects and activities.
- 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 3.6 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, utilization and storage (CCUS) technologies;
3) describe an existing national commitment to invest resources on research, development and demonstration activities in CCUS technologies;
4) describe their commitment to engage the private sector in the development and deployment of CCUS technologies; and
5) describe specific projects or activities proposed for being undertaken within the frame of the CSLF.

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

2.2. Offer.

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

2.3. Acceptance.

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

3. CSLF Governance

3.1. Appointment of Members' Representatives.

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

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:

"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 3.3 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 including revision of the CSLF Technology Roadmap 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 3.3 of the CSLF Charter, all decisions will be made by consensus of the Members.

4. CSLF-Recognized Projects

4.1. Types of Collaborative Projects.

Collaborative projects, executed and funded by separate entities independent of the CSLF and consistent with Article 1 of the CSLF Charter may be recognized by the CSLF. The CSLF Projects Interaction and Review Team (PIRT) shall determine the types of projects eligible for CSLF recognition.

4.2. Project Recognition.

The CSLF can provide recognition to CCUS projects based on the overall technical merit of the projects. Project recognition shall be a three-step process. The PIRT shall perform an initial evaluation and pass its recommendations on to the Technical Group. The Technical Group shall evaluate all projects proposed for recognition. Projects that obtain Technical Group approval 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.

Active and Completed CSLF Recognized Projects

(as of April 2019)

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 Kingdom, and United States
   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

4. **Al Reyadah CCUS Project**
   Nominators: United Arab Emirates (lead), Australia, Canada, China, Netherlands, Norway, Saudi Arabia, South Africa, United Kingdom, and United States
   This is an integrated commercial-scale project, located in Mussafah, Abu Dhabi, United Arab Emirates, which is capturing CO_2 from the flue gas of an Emirates Steel

production facility, and injecting the CO_2 for enhanced oil recovery (EOR) in the Abu Dhabi National Oil Company's nearby oil fields. The main objectives are to reduce the carbon footprint of the United Arab Emirates, implement EOR in subsurface oil reservoirs, and free up natural gas which would have been used for oil field pressure maintenance. The Al Reyadah Project includes capture, transport and injection of up to 800,000 tonnes per year of CO_2 (processed at the required specifications and pressure) and is part of an overall master plan which could also create a CO_2 network and hub for managing future CO_2 supply and injection requirements in the United Arab Emirates.
Recognized by the CSLF at its Abu Dhabi meeting, May 2017

5. **CANMET Energy Oxyfuel Project** ***(Completed)***
Nominators: Canada (lead) and United States
This was a pilot-scale project, located in Ontario, Canada, that demonstrated oxyfuel combustion technology with CO_2 capture. The project focus was on 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 oxyfuel concept. The project concluded when the consortium members deemed that the overall status of oxyfuel technology had reached the level of maturity needed for pre-commercial field demonstration. The project successfully laid the foundation for new research at CANMET on novel near-zero emission power generation technologies using pressurized oxyfuel combustion and advanced CO_2 turbines.
Recognized by the CSLF at its Melbourne meeting, September 2004

6. **Carbon Capture and Utilization Project / CO_2 Network Project**
Nominators: Saudi Arabia (lead) and South Africa
This is a large-scale CO_2 utilization project, including approx. 25 kilometers of pipeline infrastructure, which captures and purifies CO_2 from an existing ethylene glycol production facility located in Jubail, Saudi Arabia. More than 1,500 tonnes of CO_2 per day will be captured and transported via pipeline, for utilization mainly as a feedstock for production of methanol, urea, oxy-alcohols, and polycarbonates. Food-grade CO_2 is also a product, and the CO_2 pipeline network can be further expanded as opportunities present themselves.
Recognized by the CSLF at its Riyadh meeting, November 2015

7. **Carbon Capture Simulation Initiative / Carbon Capture Simulation for Industry Impact (CCSI/CCSI^2)**
Nominators: United States (lead), China, France, and Norway
This is a computational research initiative, with activities ongoing at NETL, four other National Laboratories, and five universities across the United States, with collaboration from other organizations outside the United States including industry partners. The overall objective is to develop and utilize an integrated suite of computational tools (the CCSI Toolset) in order to support and accelerate the development, scale-up and commercialization of CO_2 capture technologies. The anticipated outcome is a significant reduction in the time that it takes to develop and scale-up new technologies in the energy sector. CCSI^2 will apply the CCSI toolset, in partnership with industry, in the scale-up of new and innovative CO_2 capture technologies. A major focus of CCSI^2 will be on model validation using the large-scale pilot test information from projects around the world to help predict design and operational performance at all scales including commercial demonstrations. These activities will help maximize the learning that occurs at each scale during technology development.
Recognized by the CSLF at its Abu Dhabi meeting, May 2017

8. 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

9. 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

10. 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

11. 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

12. 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

13. 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

14. 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

15. CO_2 Capture Project – Phase 4
Nominators: United Kingdom (lead), Canada, and United States
This multistage project is a continuance of CCP3, with the goal is to further increase understanding of existing, emerging, and breakthrough CO_2 capture technologies applied to oil and gas application scenarios (now including separation from natural gas), along with verification of safe and secure storage of CO_2 in the subsurface (now including utilization for enhanced oil recovery). The overall goal is to advance the technologies which will underpin the deployment of industrial-scale CO_2 capture and storage. Phase 4 of the project will extend through the year 2018 and includes four work streams: storage monitoring and verification; capture; policy & incentives; and communications.
Recognized by the CSLF at its Riyadh meeting, November 2015

16. 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 (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

17. CO2CRC Otway Project Stage 2
Nominators: Australia (lead) and United States
This is a continuance of the Otway Stage 1 pilot project. The goal of this second stage is to increase the knowledge base for CO_2 storage in geologic deep saline formations through seismic visualization of injected CO_2 migration and stabilization. Stage 2 of the overall project will extend into the year 2020 and will include sequestration of approx. 15,000 tonnes of CO_2. The injected plume will be observed from injection through to stabilization, to assist in the calibrating and validation of reservoir modelling's predictive capability. An anticipated outcome from the project will be improvement on methodologies for the characterization, injection and monitoring of CO_2 storage in deep saline formations.
Recognized by the CSLF at its Riyadh meeting, November 2015

18. CO2CRC Otway Project Stage 3
Nominators: Australia (lead), Canada, France, Mexico, Norway, and United Kingdom
This is the third stage of a multistage CO_2 storage program, located in southwestern Victoria, Australia. The goal is to validate cost and operationally effective subsurface monitoring technologies to accelerate the implementation of commercial CCS projects. Specific objectives include developing and validating the concept of risk-based CO_2 monitoring and validation (M&V), assessing the application of innovative M&V techniques through trials against a small-scale CO_2 storage operation at the Otway research facility, and expanding the existing Otway facility such that field trials of various storage R&D are possible, including low invasive, cost-effective monitoring and migration management. An anticipated outcome is that this project will result in improved and less expensive M&V techniques which will be applicable to other onshore sites as well as sub-seabed CO_2 storage projects.
Recognized by the CSLF at its Abu Dhabi meeting, December 2017

19. CO_2 Field Lab Project ***(Completed)***
Nominators: Norway (lead), France, and United Kingdom
This was a pilot-scale project, located at Svelvik, Norway, which investigated CO_2 leakage characteristics in a well-controlled and well-characterized permeable geological formation. The main objective was to obtain important knowledge about monitoring CO_2 migration and leakage. Relatively small amounts of CO_2 were injected to obtain underground distribution data that resemble leakage at different depths. The resulting underground CO_2 distribution, which resembled leakages, was monitored with an extensive set of methods deployed by the project partners. 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

20. 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

21. 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

22. 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 CO_2 storage, both onshore and offshore.

Recognized by the CSLF at its Melbourne meeting, September 2004

23. 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.

Recognized by the CSLF at its London meeting, October 2009

24. 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

25. Dry Solid Sorbent CO_2 Capture Project

Nominators: Korea (lead), and United Kingdom

This is a pilot-scale project, located in southern Korea, which is demonstrating capture of CO_2 from a 10 megawatt power plant flue gas slipstream, using a potassium carbonate-based solid sorbent. The overall goal is to demonstrate the feasibility of dry solid sorbent capture while improving the economics (target: US$40 per ton CO_2 captured). The project will extend through most of the year 2017. There will be 180 days continuous operation each year with capture of approx. 200 tons CO_2 per day at more than 95% CO_2 purity.

Recognized by the CSLF at its Riyadh meeting, November 2015

26. 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

27. Enabling Onshore CO_2 Storage In Europe (ENOS)

Nominators: Italy (lead), Australia, Canada, France, the Netherlands, Norway, Romania, and the United Kingdom

This is a multi-faceted project whose objectives are to provide crucial advances to help foster onshore CO_2 storage in Europe through (a) developing, testing and demonstrating key technologies specifically adapted to onshore storage, and (b) contributing to the creation of a favorable environment for onshore storage across Europe. The European Union-funded project considers Europe in a broad context, though research will mainly be based on data from the Hontomin pilot site in Spain, two oil and gas fields in the Netherlands and the Czech Republic, and two field laboratories where CO_2 leakage will be simulated. Overall, ENOS has 29 partner research organizations located in 17 countries throughout Europe. Project activities include CO_2 injection testing in order to validate technologies related to reservoir monitoring, preservation of potable groundwater and terrestrial/aquatic ecosystems, and detection of any CO_2 leakage. In addition, the project will lead to increased data availability for improved site characterization and increased understanding and prevention of induced seismicity (which is crucial in an onshore storage context). The project also has a goal of integrating onshore CO_2 storage with local economic activities and of engaging researchers with local communities.

Recognized by the CSLF at its Melbourne meeting, October 2018

28. 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

29. Fort Nelson Carbon Capture and Storage Project ***(Completed)***

Nominators: Canada (lead) and United States

This was a large-scale project in northeastern British Columbia, Canada, which developed a feasibility study for a large natural gas-processing plant for CCS into deep saline formations of the Western Canadian Sedimentary Basin (WCSB). Goals of the project were to verify and validate the technical and economic feasibility of using brine-saturated carbonate formations for large-scale CO_2 injection and show that robust monitoring, verification, and accounting (MVA) of a brine-saturated CO_2 sequestration project can be conducted cost-effectively. The project's feasibility study included a risk-based approach to define the MVA strategy, modeling and simulation, site characterization, risk assessment, and development of a cost-effective MVA plan.

Recognized by the CSLF at its London meeting, October 2009

30. 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

31. 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

32. 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

33. 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

34. 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

35. 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

36. 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

37. 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

38. 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

39. 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

40. Lacq Integrated CCS Project ***(Completed)***

Nominators: France (lead) and Canada

This was an intermediate-scale project that tested and demonstrated an entire integrated CCS process, from emissions source to underground storage in a depleted gas field. The project captured and stored 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 was demonstrate the technical feasibility and reliability of the integrated process, including the oxyfuel boiler, at an intermediate scale and also included geological storage qualification methodologies, as well as monitoring and verification techniques, to prepare for future larger-scale long term CO_2 storage projects.
Recognized by the CSLF at its London meeting, October 2009

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

42. National Risk Assessment Partnership (NRAP)
Nominators: United States (lead), Australia, China, and France
This is a risk assessment initiative, with activities ongoing at NETL and four other National Laboratories across the United States, including collaboration with industry, regulatory organizations, and other types of stakeholders. The overall objective is development of defensible, science-based methodologies and tools for quantifying leakage and seismic risks for long-term CO_2 geologic storage. The anticipated outcome is removal of key barriers to the business case for CO_2 storage by providing the technical basis for quantifying long-term liability. To that end, NRAP has developed and released a series of computational tools (the NRAP toolset) that are being used by a diverse set of stakeholders around the world. The toolset is expected to help storage site operators design and apply monitoring and mitigation strategies, help regulators and their agents quantify risks and perform cost-benefit analyses for specific CCS projects, and provide a basis for financiers and regulators to invest in and approve CCS projects with greater confidence because costs long-term liability can be estimated more easily and with greater certainty.
Recognized by the CSLF at its Abu Dhabi meeting, May 2017

43. Norcem CO_2 Capture Project ***(Completed)***
Nominators: Norway (lead) and Germany
This project, located in southern Norway at a commercial cement production facility, conducted testing of four different post-combustion CO_2 capture technologies at scales ranging from very small pilot to small pilot. Technologies evaluated were 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 cement production facility flue gas. Objectives of the project were 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. Focal areas included 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

44. NET Power 50 MW_{th} Allam Cycle Demonstration Project

Nominators: United States (lead), Japan, Saudi Arabia, and United Kingdom

This is a capture-only large-scale pilot project, located in La Porte, Texas in the United States, whose overall objective is to demonstrate the performance of the Allam power cycle. The Allam Cycle is a next-generation gas turbine-derived power cycle that uses high-pressure CO_2 instead of steam to produce power at low cost and with no atmospheric emissions. The project includes construction and operation of a 50 MW_{th} natural gas-fueled pilot plant and also design of a much larger proposed commercial-scale project. The anticipated outcome of the project is verification of the performance of the Allam Cycle, its control system and components, and purity of the produced CO_2 with learnings being used in the design of a future commercial-scale project using this technology.

Recognized by the CSLF at its Tokyo meeting, October 2016

45. Oxy-Combustion of Heavy Liquid Fuels Project

Nominators: Saudi Arabia (lead) and United States

This is a large pilot project (approx. 30-60 megawatts in scale), located in Dhahran, Saudi Arabia whose goals are to investigate the performance of oxy-fuel combustion technology when firing difficult-to-burn liquid fuels such as asphalt, and to assess the operation and performance of the CO_2 capture unit of the project. The project will build on knowledge from a 15 megawatt oxy-combustion small pilot that was operated in the United States by Alstom. An anticipated outcome from the project will be identifying and overcoming scale-up and bottleneck issues as a step toward future commercialization of the technology.

Recognized by the CSLF at its Riyadh meeting, November 2015

46. 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

47. Plant Barry Integrated CCS Project ***(Completed)***

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

This pilot-scale fully-integrated CCS project, located in southeastern Alabama in the United States, brought 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 25 megawatts of power production was used to demonstrate a new amine-based process for capture of approximately 550 tons of CO_2 per day. A 19 kilometer pipeline transported the CO_2 to a deep saline storage site. The project successfully met its objectives of gaining knowledge and experience in operation of a fully integrated CCS large-scale process, conducting 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 testing CO_2 monitoring technologies. The CO_2 capture technology utilized in the project is now being used at

commercial scale.
Recognized by the CSLF at its Washington meeting, November 2013

48. 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

49. 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

50. 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

51. SECARB Early Test at Cranfield Project ***(Completed)***
Nominators: United States (lead) and Canada
This was a large-scale project, located in southwestern Mississippi in the United States, which involved 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 was on the CO_2 storage and monitoring aspects. The project promoted the building of experience

necessary for the validation and deployment of carbon sequestration technologies in the United States, and increased technical competence and public confidence that large volumes of CO_2 can be safely injected and stored. Components of the project also included public outreach and education, site permitting, and implementation of an extensive data collection, modeling, and monitoring plan. This "early" test sets the stage for subsequent large-scale integrated projects involving post-combustion CO_2 capture, transportation via pipeline, and injection into deep saline formations.
Recognized by the CSLF at its Warsaw meeting, October 2010

52. South West Hub 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

53. Tomakomai CCS Demonstration Project

Nominators: Japan (lead), Australia, Canada, France, Norway, Saudi Arabia, United Kingdom, and United States
This is an integrated large-scale pilot project, located at a refinery complex in Tomakomai city on the island of Hokkaido in Japan, which is capturing CO_2 from the refinery's hydrogen production unit with a steam methane reformer and a pressure swing adsorption process, and injecting the CO_2 by two directional wells to the nearby offshore sub-seabed injection site. The overall objective is to demonstrate the technical viability of a full CCS system, from capture to injection and storage in saline aquifers. This will contribute to the establishment of CCS technology for practical use in Japan and set the stage for future deployments of commercial-scale CCS projects. The project includes capture and injection of up to about 100,000 tonnes per year of CO_2 for three years and a comprehensive measurement, monitoring and verification (MMV) regime for the injected CO_2. The project also includes a detailed public outreach effort which has engaged local stakeholders and increased community awareness about CCS and its benefits.
Recognized by the CSLF at its Tokyo meeting, October 2016

54. 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

55. Zama Acid Gas EOR, CO_2 Sequestration, and Monitoring Project ***(Completed)***

Nominators: Canada (lead) and United States

This was a pilot-scale project that involved utilization of acid gas (approximately 70% CO_2 and 30% hydrogen sulfide) derived from natural gas extraction for enhanced oil recovery. Project objectives were 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 resulted in sequestration of about 85,000 tons of CO_2 over the life of the project.

Recognized by the CSLF at its Paris meeting, March 2007

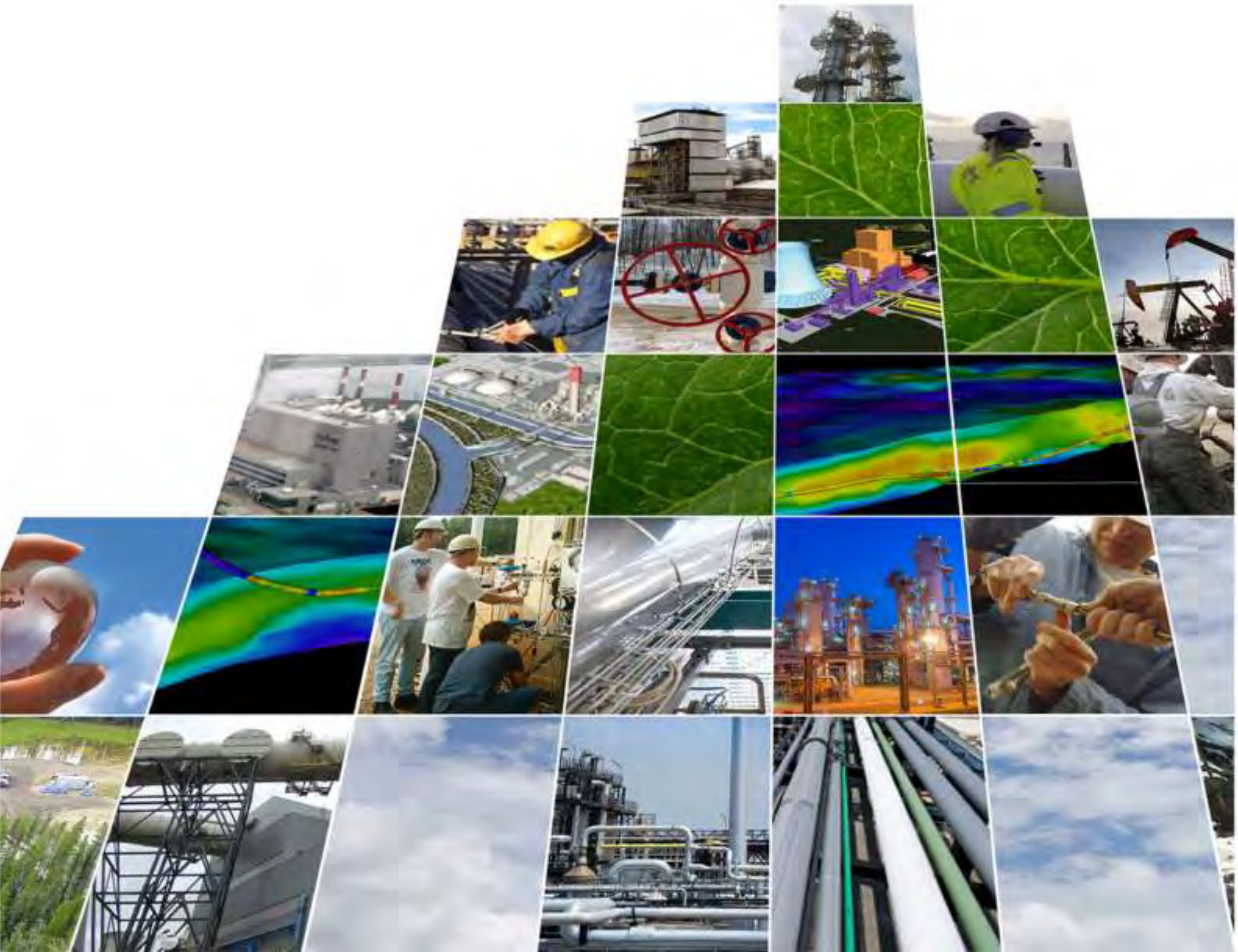
Note: “Lead Nominator” in this usage indicates the CSLF Member which proposed the project.

carbon sequestration leadership forum

2017

Carbon Sequestration

TECHNOLOGY ROADMAP



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Executive Summary

The Carbon Sequestration Leadership Forum (CSLF) *Technology Roadmap 2017* aims to provide recommendations to Ministers of the CSLF member countries on technology developments that are required for carbon capture and storage (CCS) to fulfill the CSLF mission to facilitate the development and deployment of CCS technologies via collaborative efforts that address key technical, economic, and environmental obstacles.

With the release of this technology roadmap, the CSLF aspires to play an important role in reaching the targets set in the Paris Agreement by accelerating commercial deployment and to set key priorities for research, development, and demonstration (RD&D) of improved and cost-effective technologies for the separation and capture of carbon dioxide (CO_2); its transport; and its long-term safe storage or utilization.

Key Findings

Based on reviews of several status reports on CCS and technical papers, as well as comments and input from international experts, the main findings of this *Technology Roadmap 2017* are as follows:

- CCS has been proven to work and has been implemented in the power and industrial sectors.
- The next 10 years is a critical period for CCS; therefore, a sense of urgency must be built to drive action.
- Unprecedented investment in CCS and other low-carbon technologies is needed to achieve the targets of the Paris Agreement.
- The main barriers to implementation are inadequate government investment and policy support/incentives, challenging project economics, and uncertainties and risk that stifle private sector investment.
- Rapid deployment of CCS is critical in the power sector in both Organisation for Economic Co-operation and Development (OECD) and non-OECD countries, as well as in industries other than the power sector, especially those industries for which CCS is the most realistic path to decarbonization.
- Negative CO_2 emissions can be achieved by using a combination of biomass and CCS.
- Costs and implementation risks can be reduced by developing industrial clusters and CO_2 transport and storage hubs.
- Members of the CSLF consider it critical that public-private partnerships facilitate material and timely cost reductions and accelerated implementation of CCS.

Analysis by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG 2017a) shows that if sufficiently strong incentives for a technology are established, the rate of build-out historically observed in industry analogues (power sector, oil and gas exploration and production, pipeline transport of natural gas, and ship transport of liquefied natural gas) has been comparable to the rates needed to achieve the 2°C Scenario (2DS) for CCS.[1] Reaching the beyond 2°C Scenario (B2DS) target will be significantly more challenging. Substantial investment in new CCS facilities from both the public and the private sectors is essential to achieve the required build-out rates over the coming decades. Governments need to establish market incentives and a stable policy commitment and to provide leadership to build public support for actions such as the following:

[1] The International Energy Agency, in *Energy Technology Perspectives 2017* (IEA 2017a), explores the potential of technologies to push emissions to a 2°C level, referred to as the 2°C Scenario (2DS), and below the level associated with a 2°C limit, referred to as the Beyond 2°C Scenario (B2DS). B2DS charts a trajectory for the energy sector resulting in a 50% chance of limiting the rise in temperature to 1.75°C.

- A rapid increase of the demonstration of all the links in the CCS chain.
- Extensive support and efforts to build and operate new plants in power generation and industry.
- Facilitation of the exchange of data and experiences, particularly from existing large-scale plants with CCS.
- Support for continued and comprehensive RD&D.
- Facilitation of industrial clusters and CO_2 transport and storage hubs.

Priority Recommendations

Governments and industries must collaborate to ensure that CCS contributes its share to the Paris Agreement's aim to keep the global temperature increase from anthropogenic CO_2 emissions to 2°C or below by implementing sufficient large-scale projects in the power and industry sectors to achieve the following:[1]

- Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) CO_2 per year by 2025 (or permanent capture and storage of 1,800 Mt CO_2).
- Long-term isolation from the atmosphere of at least 2,400 Mt CO_2 per year by 2035 (or permanent capture and storage of 16,000 Mt CO_2).

To this end, CSLF members recommend the following actions to the CSLF Ministers:

- Promote the value of CCS in achieving domestic energy goals and global climate goals.
- Incentivize investments in CCS by developing and implementing policy frameworks.
- Facilitate innovative business models for CCS projects.
- Implement legal and regulatory frameworks for CCS.
- Facilitate CCS infrastructure development.
- Build trust and engage stakeholders through CCS public outreach and education.
- Leverage existing large-scale projects to promote knowledge-exchange opportunities.
- Drive costs down along the whole CCS chain through RD&D.
- Accelerate CCS in developing countries by funding storage appraisals and technology readiness assessments.
- Facilitate implementation of CO_2 utilization.

CCS is a key technology to reduce CO_2 emissions across various sectors of the economy while providing other societal benefits (energy security and access, air pollution reduction, grid stability, and jobs preservation and creation). Policy frameworks for CCS need to include equitable levels of consideration, recognition, and support for CCS on similar entry terms as other low-carbon technologies and reduce commercial risks. To support the deployment of CCS, it is critical to facilitate innovative business models for CCS by creating an enabling market environment. Fit-for-purpose and comprehensive legal and regulatory frameworks for CCS are needed on a regional scale (e.g., the London Protocol to provide for offshore cross-border movement of CO_2). Strategic power and industrial CO_2 capture hubs and clusters, with CO_2 transportation and storage infrastructure, including early mapping matching sources to sinks and identification and characterization of potential storage sites, will also be needed. CCS stakeholder engagement remains critical to implementation and is aimed at building trust, addressing misconceptions, and supporting educators and community proponents of CCS projects, while improving the quality of communication.

RD&D for novel and emerging technologies is required along the whole CCS chain, as shown by the Mission Innovation workshop on Carbon Capture, Utilization, and Storage held in September 2017. The same holds for knowledge sharing. These efforts should be targeted to provide the exchange of design, construction, and operational data, lessons learned, and best practices from existing large-scale projects. The sharing of best practices continues to be of highest value and importance to driving CCS forward while bringing costs down. CO_2 utilization can be facilitated by mapping opportunities; conducting technology readiness assessments; and resolving the main barriers for technologies, including life cycle assessments and CO_2 and energy balances.

Governments have a critical role in accelerating the deployment of CCS.

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1. Introduction

1.1. Objective and audience

The objective of the Carbon Sequestration Leadership Forum (CSLF) *Technology Roadmap 2017* is to provide recommendations to Ministers of the CSLF member countries on technology developments that are required for carbon capture and storage (CCS) to fulfill the CSLF mission to facilitate the development and deployment of CCS technologies via collaborative efforts that address key technical, economic, and environmental obstacles.

The recommendations in this roadmap are directed to CSLF Ministers and their climate and energy policymakers. The CSLF Technical Group has proposed this roadmap for the CSLF Policy Group to consider as formal input into the 2017 communiqué of the biennial CSLF Ministerial meeting.

With the release of this technology roadmap, the CSLF aspires to play an important role in reaching the targets set in the Paris Agreement by accelerating commercial deployment and to set out key priorities for research, development, and demonstration (RD&D) of improved and cost-effective technologies for the separation and capture of carbon dioxide (CO_2), its transport, and its long-term safe storage or utilization.

1.2. Background

The International Energy Agency (2016a, b) and the Global Carbon Capture and Storage Institute (2015a, 2016a) state that CCS can significantly contribute to the achievement of Paris Agreement targets adopted at the 21st Conference of the Parties in December 2015: “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change” (UNFCCC 2015). The importance of CCS to mitigate the global economic cost of achieving a 2°C goal was highlighted by the Intergovernmental Panel on Climate Change (IPCC 2014), which found that achieving an atmospheric concentration of 450 parts per million (ppm) CO_2 without CCS is more costly than for any other low-carbon technology, by an average of 138%. Further, only four of 11 models that included CCS as an optional mitigation measure could produce scenarios that successfully reached the targeted concentration of 450 ppm without CCS, emphasizing that CCS is an important low-carbon energy technology.

1.3. Terminology

For the purpose of this document, the following definitions apply:

- The term carbon capture and storage (CCS) is used when CO_2 is captured from its source of production and transported to a geologic storage site for long-term isolation from the atmosphere.
- The term carbon capture, utilization, and storage (CCUS) is used when the CO_2 is used before being geologically stored permanently from a climate change perspective. This may include instances in which CO_2 is used to enhance the production of hydrocarbon resources (such as CO_2-enhanced oil recovery) or in the formation of minerals or long-lived compounds from CO_2, thereby permanently isolating the CO_2 from entering the atmosphere.
- Carbon capture and utilization (CCU) is used when the CO_2 is stored only temporarily. This includes applications in which CO_2 is reused or used only once while generating some additional benefit. Examples are urea and algal fuel formation or greenhouse utilization.

CCUS is a subset of CCS, and only the term CCS will be used in this document, except in section 3.4.

For a CO_2-usage technology to qualify for reduction of CO_2 emissions (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. It is likely that CCUS and CCU will have limited contributions to the mitigation challenge, of the order of 4%–8% for CO_2-enhanced oil recovery (CO_2-EOR) and 1% for chemical conversion of CO_2 (Mac Dowell et al. 2017). Therefore, CCU and particularly CCUS in the form of CO_2-EOR may be seen as a means of securing financial support for the early deployment of CCS in the absence of sufficient carbon prices or other incentives to deploy CCS, thus helping accelerate technology deployment (Mac Dowell et al. 2017). For example, if CO_2 from a slipstream of flue gas is used for utilization, this may contribute to reducing the cost of CO_2 capture, thus acting as a driver for the development of capture projects and transport and storage infrastructure. CCU can contribute to reduced CO_2 emissions if the CO_2 replaces new, fresh hydrocarbons as a source for carbon. In such circumstances the total carbon footprint, including energy requirements for the conversion process, must be documented (e.g., through a full life cycle analysis).

If the goals of the Paris Agreement are to be met, the scale of deployment would require the greater parts of CO_2 to be geologically stored, through CCS.

1.4. Major differences between 2013 and 2017 roadmaps

The major change in the *Technology Roadmap 2017* is new time horizons for medium- and long-term recommendations and targets: 2025 and 2035, compared with 2030 and 2050. The change emphasizes that the CSLF Technical Group recognizes a need for accelerated implementation of CCS.

Other changes are mainly found in section 3.1. and section 3.2. In the chapter on capture, explanations relating to technology types, which are described in referenced documents, have been kept to a minimum. There is a renewed emphasis on CCS applied to industrial processes, including hydrogen production and biomass, as well as on learnings from large-scale projects. The section on transport and infrastructure has been expanded, with an emphasis on the development of industrial clusters and storage hubs.

2. The Importance of Deploying CCS

2.1. The need to reduce CO_2 emissions

In 2014 total energy-related direct global emissions of CO_2 amounted to approximately 34,200 megatonnes (Mt), of which 8,300 Mt CO_2/year were direct emissions from industry and 13,600 Mt CO_2/year were direct emissions from the power sector (IEA 2017a).[2]

To reach the Paris Agreement's 2°C target, the International Energy Agency (IEA) estimates that global CO_2 emissions must be reduced to just below 9,000 Mt CO_2/year by 2060, a reduction of more than 60% compared to 2014, and must fall to net zero by no later than 2100 (IEA 2017a). In the Beyond 2°C Scenario (B2DS), the power sector reaches net negative emissions after 2045, and the whole energy sector reaches net zero in 2060. In B2DS, CCS is critical in reducing emissions from the power and industrial sectors and delivering negative emissions when combined with bioenergy. Reaching the significantly more ambitious vision of the Paris Agreement 1.5°C target would require faster and deeper CO_2 emissions reductions across both the energy supply and demand sectors.

Emissions Reduction Scenarios

Energy Technology Perspectives 2017 (IEA 2017a) explores the potential of technologies to push emissions to a 2°C level, referred to as the 2°C Scenario (2DS), and below the level associated with a 2°C limit, referred to as the Beyond 2°C Scenario (B2DS). B2DS charts a trajectory for the energy sector resulting in a 50% chance of limiting the rise in temperature to 1.75°C.

The Reference Technology Scenario (RTS) takes into account today's commitments by countries to limit emissions and improve energy efficiency, including the nationally determined contributions pledged under the Paris Agreement. By factoring in these commitments and recent trends, the RTS already represents a major shift from a historical "business as usual" approach with no meaningful climate policy response. The RTS requires significant changes in policy and technologies in the period to 2060 as well as substantial additional cuts in emissions thereafter. These efforts would result in an average temperature increase of 2.7°C by 2100, at which point temperatures are unlikely to have stabilized and would continue to rise.

2.2. The importance of CCS, the industrial sector, and negative emissions

In the IEA 2°C Scenario (2DS), CCS will account for 14% of the accumulated reduction of CO_2 emissions by 2060 and 32% of the reduction needed to go from 2DS to B2DS by 2060 (IEA 2017a). Major cuts must be made in all sectors in addition to the power sector. The industrial sector will have to capture and store 1,600 Mt CO_2/year in the 2DS and 3,800 Mt CO_2/year in the B2DS by 2060, yet the sector is still the largest contributor to accumulated CO_2 emissions to 2060 and the major CO_2 source in 2060. CCS is already happening in industries such as natural gas processing, fertilizer production, bioethanol production, hydrogen production, coal gasification, and iron and steel production (GCCSI 2016b). In addition, the demonstration of CO_2 capture unit on a waste incineration plant has taken place in Japan (Toshiba 2016), and small-scale testing has taken place in Norway (City of Oslo 2016). In 2060, CCS is expected to make up 38% of total emissions reductions in industry between the Reference Technology Scenario (RTS) and B2DS, and somewhat less than half this amount between RTS and 2DS (IEA 2017a), showing that CCS will be a critical technology for many emissions-intensive industries.

There is a high likelihood that the 2DS and, in particular, the B2DS, cannot be achieved without the deployment of "negative emissions technologies" at scale (IPCC 2014; IEA 2017a). There are several technologies that have the potential to contribute to the reduction of atmospheric CO_2 levels; each of these, however, brings its own uncertainties, challenges, and opportunities. Included among them are reforestation, afforestation (photosynthesis), direct air capture, and bioenergy coupled with CCS (i.e., CCS applied to the conversion of biomass into final energy products or chemicals). In the B2DS,

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2 Total greenhouse gas emissions were significantly higher, at approximately 49 gigatonnes CO_2 equivalent in 2010 (IPCC 2014).

almost 5,000 Mt CO_2 are captured from bioenergy, resulting in negative emissions in 2060 (IEA 2017a).

2.3. The urgency to increase the pace in deploying CCS

In 2012 the IEA expressed the view that "development and deployment of CCS is seriously off pace" (IEA 2012). Despite the fact that several large-scale CCS projects have come into operation since 2012 (see GCCSI 2015a, 2016a; IEA 2016b; and section 3) and that the IEA's estimated contribution from CCS by 2050 is 14% of the accumulated global abatement needed by 2060, the IEA (2016a, 2017a) strongly calls for increased efforts in implementing CCS: "An evolution in the policy approach to deploying CCS, as well as an increase in public-sector commitment, will be needed to reach ambitious climate targets such as those behind the 2DS and B2DS. Deploying CCS at the pace and scale envisaged in the 2DS and the B2DS requires targeted support for the different elements of the CCS chain and responses to the commercial, financial and technical challenges. Governments can encourage the uptake of CCS and leverage private investment by recognizing and supporting CO_2 transport and storage as common user infrastructure, critical to a low-carbon economy" (IEA 2017a).

The IEA is supported by the Global Carbon Capture and Storage Institute (GCCSI), which in its 2015 report on the global status of CCS (2015a) finds that "While CCS has made great progress this decade, it is abundantly clear that we must sharply accelerate its deployment." Key findings of the 2015 report may be summarized as follows:

- CCS is vital to meet climate goals.
- Only CCS can reduce direct CO_2 emissions from industry at scale.
- CCS has proved operational viability.
- CO_2 storage capabilities are demonstrated.
- CO_2 storage resources are significant.
- CCS costs will have to come down from 2016 levels.
- Excluding CCS will double the cost of mitigation.

Four international organizations have underlined the need for clear messages on CCS deployment to the CSLF ministers:

- Plans submitted by Mission Innovation members show that 19 of its 23 members (including the European Commission) list CCS as a focus area for clean energy research and development (Mission Innovation 2017).[3] A workshop organized by Mission Innovation identified priority research needs for CO_2 capture, storage, and utilization (Mission Innovation 2018).
- The World Resources Institute supported widespread implementation of CCS (WRI 2016).
- The Oil and Gas Climate Initiative announced one billion US dollars in funding for climate investments over a 10-year period (OGCI 2016), of which a significant proportion of this fund will be available for CCS projects (CCSA 2016).
- The Clean Energy Ministerial at its 8th meeting in Beijing, China, in June 2017 underlined the need for clear messages on CCS deployment (IEA 2017b).

The challenge can be illustrated by the fact that large-scale CCS projects in operation and or under construction in 2017 have a CO_2 capture capacity of about 40 Mt CO_2/year (GCCSI 2016a), whereas the required targets set by the IEA (2017a) for the 2DS and the B2DS are much higher (figure 2.1). The figure shows that the total captured and stored CO_2 will have to reach approximately 1,800 Mt CO_2 by 2025 and 16,000 Mt CO_2 by 2035 for the 2DS to be delivered. For the B2DS, the 2025 target is 3,800 Mt CO_2 and the 2035 target is almost 26,000 Mt CO_2.

[3] At the 21st Conference of the Parties, held in Paris, France, in December 2015, 20 countries plus the European Union joined Mission Innovation and pledged to double clean energy research and development funding in 5 years.

Scenario	2025	2030	2035	2040	2045	2050	2055	2060
2DS	0.42	1.16	2.41	3.79	5.01	5.43	5.83	6.65
B2DS	0.91	2.00	3.62	5.74	7.52	8.42	9.71	10.94

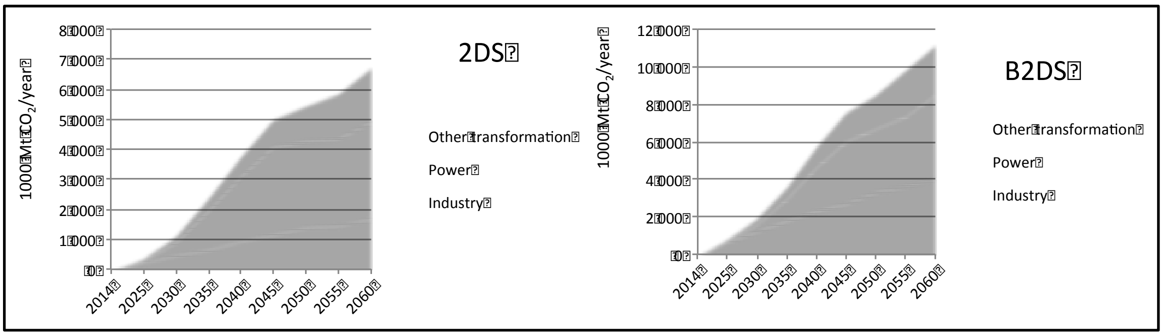

Figure 2.1. *CO_2 captured and stored per year to achieve the 2°C Scenario (left panel) and Beyond 2°C Scenario (right panel), in 1,000 Mt CO_2/year (after IEA 2017a).*

Capturing and storing 420 Mt CO_2/year by 2025 requires a considerable acceleration of deployment of CCS projects. In order for large-scale CCS deployment to take place, it is necessary to move from project-by-project thinking to systems thinking. Although the momentum for deploying CCS has slowed, and renewed national commitments and strengthened policy settings will be essential, it may still be possible to achieve the deployment needed. A review by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG 2017a) finds that the rate of build-out in industry analogues has been comparable to the rates now needed for CCS in the 2DS. The study shows that, if sufficiently strong incentives for a technology are established, industry has historically achieved the rapid build-out rates required for the projected scale of deployment. Although the analogues have limitations, the study shows that it may be technically feasible to realize the anticipated CCS build-out rates. However, substantial and perhaps unprecedented efforts from both the public and the private sectors will be required to deliver and maintain the anticipated CCS build-out rates over the coming decades. These efforts will include market incentives, stable policy commitment, government leadership, and public support. Achieving the B2DS will be significantly more challenging.

Thus, CCS will be needed in many sectors if the Paris Agreement targets are to be achieved, and more needs to be done to accelerate CCS at the pace needed to meet these ambitions. The CSLF Technical Group considers that some reasons for the slow implementation of CCS include the following:

- The complexity of large integrated CCS projects.
- Insufficient financial support for commercial-scale deployment.
- A lack of business cases and models.
- High comparative costs under weak national levels of carbon constraints.
- Localized opposition stakeholder challenges, limited knowledge, and support of the technology.

2.4. Nontechnical measures needed to accelerate the pace of CCS deployment

The CSLF mission clearly expresses a commitment to facilitate CCS as a tool to combat climate change. Technical as well as nontechnical measures are required to accelerate the deployment of CCS as a mitigation tool for global warming. Pure policy measures are not part of this technology roadmap, but there is not always a clear distinction between policy and technical measures. The combined policy/technical measures include but are not limited to the following:

- Demonstrate the value proposition of CCS as a key technology to reduce CO_2 emissions across various sectors of the economy while providing other societal benefits (energy security; access;

and additional environmental benefits, such as air pollution reduction, grid stability, and jobs preservation and creation).

- Develop policy frameworks that incentivize investment in CCS and reduce commercial risks.
- Identify and create markets that can support a business case for CCS investment.
- Implement fit-for-purpose legal and regulatory frameworks in key regions where CCS is required to be developed, including frameworks to allow CO_2 transport and storage across marine borders (the London Protocol for cross-border movement of CO_2).
- Develop strategic hubs, including mapping matching sources and sinks of CO_2, transportation, and storage infrastructure.
- Accelerate social engagement by enhancing CCS public outreach and education to build trust, reduce and tackle misconceptions, and support educators as well as community proponents of CCS projects (see also GCCSI 2016a).

The Carbon Capture and Storage Association has also identified other nontechnical steps to support the implementation of CCS (CCSA 2013). Although written for the United Kingdom, the steps have international relevance.

For bio-CCS, nontechnical issues that fall outside the scope of this technology roadmap include the following:

- Greenhouse gas reporting frameworks and emissions pricing schemes do not account for negative emissions in several, if not most, jurisdictions.
- There is a significant span in the estimates of the potential scale of bio-CCS, resulting from a limited understanding of the implications of, and interactions between, water and land use, food production, total energy use and greenhouse gas emissions, the climate system, and biodiversity and ecosystems.
- Health and social implications, particularly in relation to other emissions and discharges, like particulate matter, may lead to increased negative impacts unless precautions are taken (Kemper 2015).
- Stimulating bioenergy stakeholders to consider CCS in the sector, through targeted incentives and a nonpenalizing accounting methodology.

Since the *CSLF Technology Roadmap 2013*, there have been developments in the application of regulations in terms of projects applying for permits, and in reviews of regulation such as the European Union CCS Directive. Such activities are most useful to test the regulatory regimes. Storage permits have been successfully awarded to projects in the United States, Canada, Japan, the Netherlands, Norway, and the United Kingdom. The European Union CCS Directive was reviewed in 2014 and found fit for purpose, so no amendments were made.

A major development not covered in the *CSLF Technology Roadmap 2013* was the adoption by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) of CCS as an eligible project-level activity in the Clean Development Mechanism (CDM) under the Kyoto Protocol. In 2011 a set of rules specific to CCS were agreed on, to allow CCS projects located in developing countries to generate tradable carbon offsets for developed country Parties to use against their emissions reduction commitments under the Kyoto Protocol. It is widely anticipated that future mechanisms developed under the UNFCCC for developing countries will follow the principles established by these CCS CDM rules (modalities and procedures).

Despite these positive developments, there is still much work to do. Many countries that have expressed an interest in using CCS to reduce emissions have yet to develop regulatory frameworks, while in others, regulatory frameworks remain untested.

One opportunity, as highlighted in the United States, is the replacement of natural CO_2 with CO_2 captured from power or industrial plants to enhance oil production (CO_2-EOR), resulting in net CO_2 storage outcomes. Projects employing CO_2-EOR, particularly in the United States, Canada, and the Middle East, are operating under existing hydrocarbon legal and regulatory regimes and not regimes specifically designed for CO_2 storage. Should these projects wish to be recognized for storing CO_2, transitional regulatory arrangements will need to be considered to require operators to address storage-focused performance objectives. The International Organization for Standardization (ISO) Technical Committee on CCS (TC 265), which was approved by the members in 2011 and started its work in 2012, is working on this issue.

Similarly, cross-border offshore projects remain an issue, unless the CO_2 is used for enhanced oil recovery (EOR). This includes capturing CO_2 in one jurisdiction and/or transporting and storing it in another. For those jurisdictions without suitable offshore storage options, this will be an important issue. The London Protocol has its cross-boundary amendment and guidance in place, but its application into force awaits the slow ratification of the export amendment.

Long-term liability continues to be highlighted as an issue of concern to many policymakers, regulators, investors, and project proponents. Some of the legal and regulatory models developed in the past 10 years have established liability rules and compensation mechanisms that address the entire life cycle of a CCS project, including the post-closure period. However, for these frameworks, it remains to be seen whether closure certificates (and the like) can be successfully obtained and owners' liabilities practically limited (via transfers, indemnifications, and so on).

There is a considerable activity underway in the ISO that could support future development of regulations for the components of the CCS chain. ISO TC 265 has established six working groups, on capture, transport, storage, quantification and verification, cross-cutting issues, and CO_2-EOR, with the intent to develop a range of standards. It published an international standard on CO_2 transport in 2016, and it is expected to publish an international standard on CO_2 geological storage in 2017 and an international standard on CO_2-EOR in late 2018.[4]

[4] More information on recent regulatory developments can be found in Dixon, McCoy, and Havercroft (2015).

3. Technology Needs

3.1. Capture

This chapter identifies technology needs for CO_2 capture from point sources (for example > 0.1 Mt CO_2/year) in the power and industrial sectors. It starts with a brief assessment of the present situation.[5] An overview of large-scale CCS projects can be found in the GCCSI database (https://www.globalccsinstitute.com/projects/large-scale-ccs-projects). Below only a few are mentioned.

3.1.1. Power

Some power projects have become operational, or are close to being operational, since the issue of the *CSLF Technology Roadmap 2013*, including Boundary Dam, Canada (post-combustion with absorption; a summary is provided in IEAGHG 2015a) and Petra Nova, United States (power and post-combustion capture with chemical absorption). Also, several demonstration capture plants have been operating for many years, including Plant Barry, United States (power and post-combustion with absorption); Boreyong, Korea (power and post-combustion with solvent absorption); Hadong, Korea (power and post-combustion with solid sorbent adsorption); and Huaneng Greengen, China (power with integrated gasification combined cycle pre-combustion capture). Dedicated test facilities for the capture of CO_2 have been established in Australia, Canada, China, Norway, the United Kingdom, France, Spain, and the United States, for example. The scale of these is generally up to 20–30 megawatts (MW), or a capture capacity up to the of order of one hundred thousand tonnes of CO_2/year. Most are based on post-combustion and oxy-combustion technologies.

3.1.2. Industry

There are several industrial plants where CO_2 is captured, in almost all as part of the commercial process (GCCSI 2016b). These are found in natural gas sweetening, refineries, fertilizer production, iron and steel production, and coal gasification. Several such plants have implemented CCS, including full-scale industry projects such as Quest (Shell Canada; hydrogen production, solvent-based absorption); the Air Products Port Arthur CCS project (hydrogen and CO_2 production with pressure swing adsorption and vacuum swing adsorption, respectively); and the Emirates Steel Industry (United Arab Emirates; amine-based CO_2 capture from the direct reduced iron process). In Japan, CCS on the Tomakomai refinery (GCCSI 2016d) and the first application of CO_2 capture to waste incineration (Toshiba 2016) both started in spring 2016. There are also activities for the application of CCS in the petrochemical industry in China; a cement plant in Taiwan; and concept studies for cement, waste incineration, and fertilizer plants in Norway (MPE 2016; Svalestuen, Bekken, and Eide 2017).

Several studies and reports deal with capture technologies that may be applicable to various industries, their potential to reduce emissions, and the technological as well as other barriers to their implementation.[6] Their key findings include the following:

- Some currently available technologies, in particular amine solvents, are ready to be applied in early projects in several industries.
- Oxy-combustion capture is an early-stage candidate in some industries, although there is limited operational experience.
- In industrial applications, other technologies might be favored when they allow for better integration with the existing process (e.g., direct calcination technology in cement plants).

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5 For an extensive review of CO_2 capture technologies in the power and industrial sectors, see for example the *International Journal of Greenhouse Gas Control*, Special Issue 40 (IJGCC 2015), GCCSI (2016c), ISO (2016a), and ZEP (2017a).

6 For example, UNIDO (2010), IEA and UNIDO (2011), ZEP (2013a, 2015, 2017a), ISO (2016a), DECC (2014, 2015), MPE (2016), GCCSI (2016c), IEAGHG (2013a) (iron and steel), IEAGHG (2013b) (cement), IEAGHG (2016a) (pulp and paper), IEAGHG (2017b, 2017c) (hydrogen production), and IEAGHG (2017d) (natural gas production).

- Considerable knowledge and experience from the power sector's development and implementation of CO_2 capture technologies can be transferred to a range of industries.

A study performed for the former United Kingdom Department of Energy and Climate Change (DECC 2015) indicated that as much as 36.5% of industrial CO_2 emissions in the United Kingdom may be reduced by directly employing CCS. More would be achieved through the use of CCS to decarbonize electricity and gas (e.g., via hydrogen) supplied to industry. In a roadmap towards zero emissions by 2050, the Norwegian process industries indicated that CCS can be responsible for 36% of the required cuts in CO_2 emissions, relative to a reference case with robust industrial growth (Norsk Industri 2016).

There are, however, still technology challenges related to the implementation of CCS in energy-intensive industries:

- High costs.
- Levels of uncertainty regarding investments.
- Environmental impacts as well as health and safety implications regarding waste products and toxicity.
- Increased operational complexity and risks (integration, hidden costs of additional downtime, alternative product supplies, and technology lock-in; these will be site-specific).
- New applications of existing technologies that are not yet proven at scale.
- Understanding the impact of different compositions of the feed and/or flue gases compared to the power sector.

3.1.3. Bio-CCS

Biomass absorbs CO_2 from the atmosphere as it grows. Net removal of CO_2 from the atmosphere, or negative emissions, may be achieved if the CO_2 released during conversion of biomass to chemicals or energy products is captured and stored permanently in geological formations, here referred to as bio-CCS. The biomass must be grown in a sustainable manner. The importance of bio-CCS has been highlighted by the Intergovernmental Panel on Climate Change (IPCC 2014). There are currently a number of projects in operation that capture 0.1–0.3 Mt CO_2/year, mainly from ethanol plants (Kemper 2015; Ensus 2016; CSLF 2017a). The Illinois Industrial Project, by Archer Daniels Midland Company in the United States, has from April 2017 captured 1 Mt CO_2/year. At least three of the projects sell the CO_2 for EOR, and one injects the CO_2 into a deep saline formation. The others sell the CO_2 for use in the greenhouse and food industries.

The scale of operational bio-CCS plants are orders of magnitude less than what will be needed for bio-CCS to become a major contributor to negative CO_2 emissions. Estimates of the theoretical potential of bio-CCS to remove CO_2 from the atmosphere show significant spread (for example, Kemper 2015; Williamson 2016). The scale will be limited by factors that include available biomass, competition with food production and other uses of land and water, and other end uses of biomass. Potential impacts on biodiversity and ecosystems have also been identified as issues.[7]

The CSLF (2017a) has provided an overview of bio-CCS, including technology options and pathways. The CO_2 from fermentation in the abovementioned ethanol plants is nearly pure (containing a small amount of water) and does not require the separation technologies associated with power and heat generation, and with several industrial processes. For other bio-CCS plants, the CO_2 capture technologies are in essence the same as for CCS on power, heat generation, and process industries. Thus, bio-CCS applications may allow for a relatively smooth integration into current energy systems.

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[7] Kemper (2015) gives a review of the benefits, impacts, and challenges related to bio-CCS; Mander et al. (2017) reflects on the role of bio-CCS in a whole system perspective; and Anderson and Peters (2016) gives a cautious note on the potential.

Co-combustion of fossil fuels, biomass, and domestic waste is also a bioenergy approach to which CCS can be applied (waste often contains significant levels of biogenic material). Co-combustion can often achieve better conversion efficiencies, economies of scale, and insensitivity to biomass supply variations (e.g., seasonal).

There are, however, some technical challenges related to the biomass combustion/conversion process in general that can lead to increased corrosion, slagging, and fouling (Pourkashanian, Szuhanszki, and Finney 2016) for the capture process. These include, for example, dealing with the high moisture content, diversity, variability, and impurities of biomass. Research into the less mature options, like large-scale biomass gasification, should also be pursued. Other areas where research may be needed include the following:

- Further advances in boiler and gasification technologies.
- Advanced technologies for drying biomass at the recovery site to minimize water transport costs and heating inefficiencies.
- Improved understanding of the composition of biomass feedstock and the impacts of impurities, in particular heavy metals, in the flue gas from biomass combustion on the CO_2 capture and compression systems and the scope to remove these impurities from the biomass prior to thermal conversion (Gudka et al. 2016).
- Finding the optimal size of capture and/or conversion installations for biomass conversion and combustion.
- Investment and operational costs of bio-CCS systems.
- The impact of biomass, including co-firing with fossil fuels, and aspects such as recirculation of CO_2 and CO_2 purification required in oxy-combustion systems.
- Identifying feedstocks that require limited processing.
- Ensuring compatibility with existing boiler and pollution control equipment.
- Reducing the cost of processing equipment costs and associated energy costs.

The specific processes adapted to every biomass source (vegetal, waste, and so on) and use (power and heat, paper, cement, and so on) require a considerable amount of research focusing on the heat integration of the capture unit, which is important for the overall efficiency and cost of capture.

Nontechnical issues with bio-CCS fall outside the scope of this technology roadmap. Some of these were described in section 2.4.

3.1.4. Hydrogen as a mechanism to decarbonize industries

Presently, hydrogen is used extensively in industry, mainly in ammonia production and in oil refineries, where it is also used to remove sulfur and other impurities from crude oil and its products (GCCSI 2016b). Hydrogenation is also used in the food and petrochemical industries, among others. There are a few car manufacturers that offer cars running on hydrogen (Honda, n.d.; Hyundai, n.d.; Toyota, n.d.). Further, hydrogen has been assessed as a means to decarbonize cities (Northern Gas Networks 2016).

Globally, hydrogen production in 2017 depends heavily on processing fossil fuels, including natural gas, oil and coal, while at the same time producing CO_2 as an unavoidable byproduct. Even if hydrogen is produced by electrolysis and renewable energy, it is likely that some hydrogen will still have to be produced from fossil fuels for sufficiency and stability of supply.

The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) (2017b) investigated the potential of decarbonized hydrogen produced through CCS on natural gas and concluded that the process may decarbonize a number of industries. The cost of decarbonized hydrogen is currently lower than that of electrolysis-derived hydrogen from renewable energy. The technology required exists, and ZEP (2017b) provides an overview of available technologies, as well as of plants in operation. Voldsund, Jordal, and Anantharaman (2016), among others, gives more detailed technology descriptions.

Thus, there are few, if any, technical barriers to CO_2 capture associated with large-scale hydrogen production. However, continued research, development, and innovation for improved and emerging technologies for clean hydrogen production should be encouraged, including the following:

- Process intensification: more compact, efficient, and economic solutions, such as membranes and technologies for catalytic reforming of the fuel and separation of hydrogen (H_2) and CO_2.
- Process integration in the co-production of H_2 and, for example:
  - Electricity and heat production.
  - In industrial processes where H_2 or H_2-enriched natural gas can replace fossil fuel-based feedstock.

A limiting factor to large-scale deployment is that presently there is no large-scale CO_2 transport and storage infrastructure in place. ZEP (2017b) also lists a number of nontechnical recommendations, such as identifying policies and support mechanisms, identifying local clusters for synergies, investigating the potential role of clean hydrogen in Europe, and encouraging collaborations.

3.1.5. Addressing technology needs

It is important to separate between the capture system as a whole and its components, or the subsystem level. Innovation and improvements at the subsystems/components level from a very low Technology Readiness Level (TRL) can take place long after a complete system has arrived at TRL 9 (Adderley et al. 2016).

> Technology Readiness Level (TRL) describes the maturity of technology. TRL 1 spans concept studies and very basic technology research. TRL 9 usually describes a technology that is tested and qualified for deployment at industrial scale. For a review of TRL, see Carbon Sequestration Leadership Forum (2015).

Costs for CO_2 capture can be reduced through the following:

- Applying experiences and learnings from successful as well as unsuccessful projects to support RD&D and further evolving existing CO_2 capture technologies.
- Supporting RD&D that brings out novel technologies at the subsystem/component level.
- Combinations between CCS and renewable energy (wind, solar, geothermal, hydropower, or other renewables) to supply the energy for the capture process.

Learning from experience

Cost reductions for CO_2 capture are expected to come from knowledge transfer regarding planning, design, manufacturing, integration, operation, and scale-up. The knowledge gained can give important input to achieve reduced capital expenditures and operational expenditures and provide increased confidence for deployment.

Experiences from demonstration and commercial plants may be transferrable to other industries as well as to novel capture technology. Many capture technologies are relevant to a range of applications. A network for knowledge sharing among full-scale facilities (e.g., by expanding the existing International Test Centre Network)[8] may help to increase understanding of the scale-up challenge. Such a network would explore knowledge gained and share data and experiences from existing full-scale plants in a systematic way. Knowledge sharing should include experience from the integration of CO_2 capture systems in power or industrial plants, in heat integration, environmental campaigns (such as in solvent degradation), aerosol formation, environmental control systems (sulfur oxides, nitrogen oxides, and hydrogen sulfides), experience in part-load operations and daily cycling flexibility, and even manufacturing. It could also include experiences from the impacts of CO_2 composition and impurities. It will benefit all parties if engineers and researchers are given access to

[8] The International Test Centre Network, established in 2013, has nine members from seven CSLF nations. It is a network that focuses on post-combustion using solvents. The CO_2 Technology Centre Mongstad is the largest of the member facilities, whose capacity borders on pilot and demonstration. The other members are smaller but provide useful experience with second-generation post-combustion technologies.

the information. The data collected at the plants will be instrumental in validating and improving simulation tools that help increase understanding of the process and help reduce costs. Such a network has already been established for storage. The CO_2 Storage Data Consortium is a new international network aimed at promoting data sharing from pioneering CO_2 storage projects in order to accelerate innovation and deployment of CCS.

A barrier to achieving the open exchange of information, knowledge, and experience may be the ownership of intellectual property rights. Commercial entities need to make a return on what is a significant investment, and they may not want to give their intellectual property away. Confidentiality agreements may have to be considered. However, the capture and storage programs of the United States Department of Energy (DOE) are examples in which researchers and industry meet annually to share information about their project results.[9] Also, the European Union-funded programme European Research Area Network Accelerating CCS Technology is encouraging the eight funded projects to actively collaborate where possible through knowledge-sharing workshops. Alternatively, knowledge sharing can be limited to non-proprietary and generic data, such as heat integration, heat exchangers, other support utilities, environmental issues, and flow and process simulations that the research and engineering communities can work on to bring costs down. Non-proprietary advanced solvent systems (e.g., the CO_2 Separation and Recovery Project [TNO 2012]; Manzolini et al. 2015) may also see wider deployment. Material research and fabrication may also be considered.

Novel/emerging/innovative/transformative subsystem technologies

Capture technologies are continuously in development, both with regard to improvements of currently available commercial technologies, which may be termed second or higher generations of these, as well as novel or emerging technologies. These are at very different stages of maturity, ranging from concepts or ideas through large pilots at 20–30 MW scale, or a capture capacity of up to a few hundred thousand tonnes of CO_2/year. Reviews of such technologies, including discussions of maturity in terms of TRLs, can be found in a number of sources (Abanades et al. 2015; IEAGHG 2014; ZEP 2017a; CSLF 2015). Mission Innovation (2018) has identified some research needs for CO_2 capture.

Further development of currently available and novel capture technologies, including radically new approaches, will benefit from the following:

- Stronger modularization of the capture units, which will make them more adaptable to a range of applications, capture rates, and sizes.
- Improvements in and more verification data for advanced computational tools.
- Advanced manufacturing techniques, such as 3-D printing, that have the potential to revolutionize the synthesis and functionality of advanced technologies and materials in many different fields.
- Exploring and exploiting the benefits of hybrid solutions; for example, solvents/sorbents in combinations with membranes.
- Materials research, development, and testing.
- Solvents and sorbents with reduced regeneration energy (strong reductions in electricity output penalty).
- Reduced degradation of solvents and sorbents.
- Reduced reaction time of solvents.
- Reduced environmental impacts of capture technologies (for amine-based technologies, significant improvements have been made regarding degradation and emissions).
- Improved membranes for separation of CO_2 in both high- and low-partial-pressure gas streams.
- Improved materials for looping processes.

[9] Respectively, the "CO_2 Capture Technology Project Review Meeting" and the "Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage, Oil and Natural Gas Technologies Review Meeting."

- Air separation and combustion technologies.
- Parametric design to allow scaling from the large pilot scale to commercial applications.
- Optimized overall process, system integration, and process simplification.

Development of novel capture technologies benefits from international cooperation and researcher access to top-quality research facilities. A consortium of European RD&D facilities has been established towards this end—the European Carbon Dioxide Capture and Storage Laboratory Infrastructure consortium. However, its members are mainly at the laboratory scale, whereas one challenge is to bring technologies from concept to cost-effective demonstration. In particular, bringing new capture systems, of which new technologies may be part, across the valley of death from pilot to demonstration is expensive, as it requires large test facilities. There are few such facilities, and the existing ones are mainly for solvent-based absorption technologies. Progress will require international cooperation and burden sharing. Test facilities need to be increased both in numbers and in types of technologies. The facilities should be independent of technology vendor and technology neutral. The data collected at the test facilities will be instrumental in validating and improving simulation tools.

Performance and cost evaluations of CO_2 capture technologies must be examined and interpreted with care. A common language and methodology, and transparency of methods and assumptions, is critical to the proper assessment of CCS performance and costs. Standardization is often lacking in CCS cost studies, although attempts have been made to overcome this (GCCSI 2013). ISO has issued an international standard on performance evaluation methods for post-combustion CO_2 capture integrated with a power plant (2017). Over a longer time perspective, this could be followed by other standards once technologies have matured and have been implemented.

3.1.6. Recommendations for CO_2 capture

Towards 2020:

Governments and industry should work together to:

- Reduce the avoided carbon cost (or capture cost) in dollars per tonne of CO_2 (\$/tCO_2) of currently available commercial CO_2 capture technologies for power and industry by at least 30%, while at the same time minimizing environmental impacts.
- Establish a network for knowledge sharing among full-scale facilities (e.g., by expanding the existing International Test Centre Network to share knowledge and experiences and increase understanding of the scale-up challenge).
- Resolve issues mentioned in section 3.1.2 regarding industrial CO_2 capture and bio-CCS and further develop technologies for applications and implementation in pilot plants and demonstrations.
- Increase possibilities for testing at the large pilot and demonstration scale by facilitating planning and construction of more test facilities for technologies other than solvent-based technologies.
- Fund and encourage RD&D activities for new and promising capture technologies.
- Increase activities on large-scale production of hydrogen with CCS, with the aim to develop this as a serious option in the 2025–2030 time frame.

Towards 2025:

Governments and industry should work together to:

- Fund and facilitate cross-border RD&D cooperation to bring to demonstration CO_2 capture technologies for power generation and industrial applications that have avoided cost in \$/tCO_2 (or capture cost) at least 40% below that of 2016 commercial technologies, while at the same time minimizing environmental impacts.
- Fund promising technology ideas to be tested and verified at pilot scale (1–10 MW range) and/or separating 0.01–0.1 Mt CO_2/year.

Towards 2035:

Governments and industry should work together to:

- Encourage and facilitate cross-border RD&D cooperation to bring to demonstration CO_2 capture technologies for power generation and industrial applications that capture 100% (or very close to 100%) of the CO_2 and at the same time achieve 50% reduction of avoided carbon cost in \$/tCO_2 (or capture cost) compared to 2016 commercial technologies, while minimizing environmental impacts.
- Gain experience in the integration of power plants with CCS into electricity grids that utilize renewable energy sources, seeking to develop optimal hybrid concepts with zero or negative emissions.

3.2. CO_2 infrastructure

Coping with the large volumes of CO_2 to be collected from future power plants and industrial clusters,[10] pursuant to the 2DS, will require a CO_2 infrastructure, or network, comprising both transport and storage. The CO_2 infrastructure will generally consist of capture from sources, individually or in clusters; transport to a collection hub;[11] and common transport to a common geological storage reservoir. This section will deal with the transport part and collection hubs.

It is important to note that a barrier to the rollout of international infrastructure for offshore CCS is the London Protocol's prohibition on the export of waste, which currently means that CO_2 cannot be exported for storage across marine borders. While an amendment to change this is in place, it is not in force due to very slow ratification.

3.2.1. Transport

CO_2 is being transported daily by pipelines, trucks, trains, and ships in many parts of the world, although the last three in limited amounts. In certain cases, a combination of pipelines and ships is also an alternative. GCCSI (2016e) and ZEP (2017a) give overviews of transport of CO_2 by pipelines and ships; the former also provides an overview of RD&D activities.

Pipelines are the most common method for transporting the large quantities of CO_2 involved in CCS projects. In the United States, around 7,600 kilometers (km) of onshore pipelines transport approximately 68 Mt CO_2/year (DOE NETL 2015; GCCSI 2016a). However, there is limited experience with CO_2 pipelines through heavily populated areas, and the 153 km, eight-inch pipeline at Snøhvit is the only offshore CO_2 pipeline. ISO has issued an international standard that, at an overall level, points out what is distinctive to CO_2 pipelines relative to other pipelines (ISO 2016b).

Despite the extensive experience with CO_2 pipelines, RD&D can still contribute to optimizing the systems, thereby increasing operational reliability and reducing costs. The additional RD&D work should include improved understanding and modeling of properties and the behavior of CO_2 streams, validated flow assurance tools for CO_2-rich mixtures, the impact of impurities on compression work and on pipeline materials (such as seals and valves) and corrosion, phase equilibria, and equations-of-state of complex CO_2 mixtures, as well as possible repository requirements (Munkejord, Hammer, and Løvseth 2016). Other optimization needs include improved fracture control, leakage detection, improved capabilities to model releases from pipelines carrying dense-phase CO_2 with impurities, and the identification and qualification of materials or material combinations that will reduce capital and/or operational costs. They also include effective and accepted safety measures for large supercritical pipelines, particularly in more populated areas, as has been experienced by the Barendrecht project in the Netherlands, (Feenstra, Mikunda, and Brunsting 2010). This is particularly important for clusters and plants with several units, as these will have much higher capacities than point-to-point

[10] A cluster is a geographic concentration of emission sources.

[11] A hub is a facility that collects captured CO_2 from several sources of a collective size (e.g., > 10 kilotonnes CO_2/year).

projects. Another aspect is to look at integrating low-pressure pipeline networks with high-pressure pipeline systems. Public outreach and stakeholder dialogue and communication will be important.

There are currently no commonly agreed on specifications for the quality of the CO_2 to be transported and injected, which leads to uncertainty regarding transport of CO_2 containing impurities (ISO 2016b). As a strict CO_2 specification gives little flexibility in a CO_2 transport network and will add to the cost, it seems necessary that CO_2 specifications will be identified and documented for each case.[12]

Ship transport can be an alternative to pipelines in a number of regions, especially in cases where CO_2 from several medium-sized (near-) coastal emissions sources needs to be transported to a common injection site or to a collection hub for further transport in a trunk pipeline to offshore storage. Shipment of food-quality CO_2 already takes place on a small scale (1,000–2,000 cubic meters per ship). The CO_2 is transported as a liquid at 15–18 bar and –22°C to –28°C, but for larger volumes, 6–8 bar at around –50°C may be better (Skagestad et al. 2014). Major carriers, such as Maersk Tankers (Maritime Danmark 2009), Anthony Veder (Vermeulen 2011), and Chiyoda Corporation (2011, 2012) have initiated preliminary design. A feasibility study for implementation of a full-scale industrial CCS project in Norway concluded that ship transport of CO_2 can be an enabler for realizing full-scale CCS in the country (MPE 2016; Økland 2016). This conclusion is supported by a major Dutch study (de Kler et al. 2016), a Scottish literature study (Brownsort 2015) and the study for Antony Veder (Vermeulen 2011). The studies considered ships in the range of 5,000–50,000 tonnes CO_2 capacity. The Norwegian Ministry of Petroleum and Energy (MPE) study also included 45 bar and +10°C in addition to the two abovementioned conditions.

The Norwegian feasibility studies did not identify major issues with loading and offloading of the CO_2. In the case of direct injection from ship to well, it is anticipated that this will take place from a buoy. Single point moorings and transfer technologies are available (e.g., Brownsort 2015). The extensive experience with offloading buoys in the North Sea does not cover the higher frequency of connection and disconnection that would be the case for direct injection of CO_2 from ships. This option is therefore in need of further engineering for optimization. Other needs for technology development of ship transport are linked to optimization and qualification of the first systems for large-scale projects.

Roussanaly, Bunsvold, and Hognes (2014) and Kjärstad et al. (2016) have compared transport costs by pipelines and by ships to shed light on the optimal cost solution.

The transport of smaller volumes of industrial and food-grade CO_2 has been successfully undertaken by truck and rail for more than 40 years. However, the cost of transportation by truck or train is relatively high per tonne of CO_2 compared to pipelines, so truck and rail transport may have a limited role in CCS deployment, except for small-scale CCS opportunities or pilot projects (GCCSI 2016c). Roussanaly et al. (2017) show that train-based transport of CO_2 may have site-specific cost benefits related to conditioning costs.

3.2.2. Hubs and clusters

Planning CO_2 infrastructure with hubs and clusters will have to consider the amount of collectible CO_2, how transport (including seaborne and land transport) solutions might change for a growing cluster, the integration of different capture systems and CO_2 compositions, the scale-up risks, solutions for intermediate storage, and the impact of CO_2 impurities along the whole system. Storage sites are also important, and attention must be paid to long lead times for selection, characterization, and permitting, as these factors may be project limiting.

There are presently few CCS clusters and transport networks in operation. The IEA (IEAGHG 2015b) made an in-depth review of 12 cluster and hub locations (also referred to in GCCSI 2016e), of which three are in operation—the Denver City, Gulf Coast, and Rocky Mountain hubs—all in the United States. These are CO_2-EOR systems where clusters of oilfields are fed by a network of pipelines. The other described systems are initiatives or plans for CO_2 networks in Australia, Canada, Europe (the

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12 This is one of the conclusions of the project IMPACTS, which is funded by the European Union (IMPACTS 2016).

Netherlands and the United Kingdom), and the United Arab Emirates. Studies from initiatives such as Teesside (Tees Valley), United Kingdom, and the Rotterdam Capture and Storage Demonstration Project, Netherlands, can offer experience in the design of new systems, although they have not been deployed. The Alberta Carbon Trunk Line, Canada, is under construction. In Europe, several studies have identified CCS hubs or infrastructures.[13]

Building the infrastructure necessary to handle large volumes of CO_2 requires that the industry moves on from the studies and projects mentioned above.

The United Kingdom CCS Cost Reduction Task Force (CCSA 2013) found that CO_2 transport costs could be reduced by more than 50% with the deployment of large, efficiently utilized pipelines (5–10 million tonnes CO_2 per year compared to 1–2 million tonnes per year), noting that even lower costs could be seen in the longer run if higher volumes of CO_2 from multiple large capture plants are fed into an interconnected right-sized network. Transportation of CO_2 represents a smaller part of the total costs for a CCS chain than capture and may have, relatively speaking, moderate impact on the total cost of a CCS chain, particularly for onshore pipelines (IEAGHG 2015b), although the cost may be significant in absolute money terms (Roussanaly, Brunsvold, and Hognes 2014). However, there are other potential benefits in addition to cost sharing (GCCSI 2016e; ZEP 2013b; IEAGHG 2015b), including the following:

- Lowering costs in building early infrastructure by utilizing benefits of connecting low-cost industrial sources with storage sites.
- Lowering costs by sharing infrastructure.
- Lowering the entry barriers for participating CCS projects, such as emitters with small-volume sources and emitters with limited or no access to local storage.
- Securing sufficient CO_2 for CO_2-EOR projects, which is likely to be an important element of some clusters because of the revenue it can contribute.
- Minimizing the environmental impacts associated with infrastructure development, as well as the impact on communities.
- Minimizing and streamlining efforts in relation to planning and regulatory approvals, negotiations with landowners, and public consultations.
- Sharing and utilizing surplus heat in the capture processes of industrial clusters.

In order for large-scale CCS deployment to take place, it is necessary to move from project-by-project to systems thinking. The GSSCI (2016e), ZEP (2013b; 2017c), and the IEA (IEAGHG 2015b) reveal few technology gaps for implementing CCS clusters. Most gaps, risks, and challenges are commercial and political in nature and may 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, flexibility, reliability, financing and political aspects, and last but not least, lack of business models for larger CCS systems. Some thinking on business models has started that includes the separation of CO_2 capture at the sources from the transport and storage parts (Esposito, Monroe, and Friedman 2011; Pöyry and Teesside Collective 2017; Banks, Boersma, and Goldthorpe 2017). In these models, a split of costs and risk between the government and the industry players has been explored; for example, governments taking a certain responsibility to develop transport and storage networks. A feasibility study conducted in Norway (MPE 2016) identified three possible industry sources of CO_2 (providing in total 1.3 Mt CO_2/year), with pipeline/ship transport to an onshore facility and a common storage site located 50 km from the coast. The government will investigate a model in which the state may take on certain responsibilities for cost and risks in connection with the development of the transport and storage infrastructure together with industry to advance the development of a commercial market for CO_2 storage. Another learning from the Norwegian project is that current CO_2 storage regulations must be adjusted to clarify roles and responsibilities over the lifetime of CO_2 storage projects.

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[13] For example, ZEP (2013b, 2016a); Jakobsen et al. (2017); Bellona (2016); and Brownsort, Scott, and Hazeldine (2016), the last by reuse of an existing oil pipeline.

3.2.3. Recommendations for CO_2 transport and infrastructure

Towards 2020:

Governments and industry should work together to:

On transport

- Acquire necessary data for impurities in CO_2 streams and understand the effects on pipeline materials.
- Establish and validate models that include effects as above.
- Further develop safety measures for large-scale CO_2 pipelines, including validation of dispersion models for impact assessment of incidents pursuant to leakage of CO_2 from the transport system.
- Qualify pipeline materials for use in CO_2 pipes and injection tubing when the CO_2 contains impurities.
- Optimize and qualify systems for ship transport, in particular direct offshore unloading of CO_2 to a well.
- Map the competing demands for steel and secure the manufacturing capacity for the required pipe volumes and other transport items.
- Develop systems for metering and monitoring CO_2 supplied from multiple sources with varying purity and composition that feed into a common collection and distribution system.
- Identify business cases for transportation and storage companies.

On infrastructure

- Design and initiate large-scale CO_2 hubs that integrate capture, transport, and storage, including matching of sources and sinks.
- Develop commercial models for industrial and power CCS chains.

Towards 2025:

Governments and industry should work together to:

- Implement the first large-scale (i.e., >10 Mt CO_2/year aggregate throughput) CCS chains in power, industrial, and bio-CCS. These should be focused in industrial regions that have the potential to share infrastructure, rather than focusing on individual projects.
- Implement initial shared infrastructure for a limited number of plants within industrial clusters. This should recognize that in the initial phases, volumes within these clusters may be less than one million tonnes per annum, but that expansion from this initial start will occur.

Towards 2035:

Governments and industry should work together to:

- Continue progressive rollout and expansion of full-scale CCS chains and clusters in power, industrial, and bio-CCS. This includes large-scale CO_2 transport networks that integrate CO_2 capture, transport, and storage, including matching of sources and sinks.

3.3. Storage

Storage works, as exemplified by the projects in table 3.1. These are presently operating or are expected to become operational during 2017 with pure geological storage. Five are large-scale projects (GCCSI 2016b, n.d).

Table 3.1. Projects with pure geological storage

Project	Operational from	Amount stored, Mt CO_2/year	Storage type
Sleipner	October 1996	0.9	Offshore aquifer
Snøhvit	April 2008	0.7	Offshore aquifer
Quest	November 2015	1.0	Onshore aquifer
Illinois Industrial CCS	April 2017	1.0	Onshore aquifer
Tomakomai	April 2016	0.1	Offshore aquifer
Gorgon	Autumn 2017	3.4	Offshore aquifer

The GCCSI identifies a further eight pure geological storage projects under consideration. In all, the GCCSI has identified a total of 38 large-scale projects, of which the majority are enhanced oil recovery projects.

The Sleipner storage project has been running since fall 1996 without any incidents, and it has successfully stored more than 16 million tons of CO_2 injected into the Utsira Formation in the Norwegian sector of the North Sea, demonstrating that CO_2 can be safely and securely stored in significant quantities over decades.

At Snøhvit, in the Barents Sea, CO_2 from an onshore liquefied natural gas plant is transported offshore using a 153 km pipeline and is injected via a subsea template into neighboring reservoirs, from which natural gas is produced from a depth of about 2,400 meters. It has injected around 4 Mt of CO_2. After about one year of CO_2 injection at the Snøhvit field, the well pressure increased steadily. The operator implemented corrective measures while the relevant authorities were kept informed; there was no risk for leakage of CO_2 to the seabed. The Snøhvit case illustrates how risks can be avoided with well-conceived monitoring and risk management systems.

Quest, located in Alberta, Canada, retrofitted CO_2 capture facilities to three steam methane reformers at the existing Scotford Upgrader. Launched in November 2015, Quest has the capacity to capture approximately 1 Mt/year of CO_2 annually. The captured CO_2 is transported via pipeline to the storage site for dedicated geological storage. In July 2017, Quest announced it had captured and stored 2 million tonnes of CO_2.

The Illinois Industrial CCS Project is the first CCS project in the United States to inject CO_2 into a deep saline formation at a scale of 1 Mt/year, and it is also the world's first large-scale bio-CCS project. Its CO_2 source is derived from a corn-to-ethanol process.

The Gorgon CO_2 Injection Project in Australia plans to commence operations in autumn 2017, with injection of CO_2 at a depth of about 2 km below Barrow Island, off the northwest coast of Australia. The injection rate will be 3.4–4.0 Mt/year for at least 30 years.

In Japan, the Tomakomai Project has injected approximately 0.1 Mt CO_2/year into an offshore aquifer since April 2016. The CO_2 is captured at the hydrogen unit at a refinery. The CO_2 is injected by two deviation wells drilled from onshore. The injection zones are more than 1,000 meters long. The monitoring system at Tomakomai includes three observation wells, seismometers for earthquake monitoring and marine monitoring surveys with side-scan sonar, water sampling, a seabed profiler, current meters, and sampling and observations of benthos.

In addition, the CO_2 re-injection K12B project on the Dutch continental shelf has been operating since 2004, injecting 90,000 tonnes CO_2 during continuous natural gas production. Monitoring systems have been in place and tested since 2007. From 2015, monitoring was expanded to include tracers (GDF Suez, n.d.).

The continued deployment of commercial-scale projects is essential for the accelerated technology development needed to reduce costs and enhance confidence in CO_2 storage as a safe and permanent solution for curbing CO_2 concentrations in the atmosphere. In addition, new business models are needed to make CCS commercially attractive for the operators. CO_2-EOR is one opportunity for improving the business case, and hydrogen production can be another. Nevertheless, CCS depends on significant investments.

The identification of suitable storage sites and validation of storage capacity remain a challenge, especially where geological and geophysical data coverage is sparse. Moreover, the methods to evaluate CO_2 capacity should be improved to include dynamic properties to reduce potential errors in this evaluation. However, based on evaluations of storage capacities, for example in Australia, Brazil, China, South Africa, the United Kingdom, the United States, and the Nordic countries, it is anticipated that sufficient storage is available for several decades.[14]

The United Nations Economic Commission for Europe Expert Group on Resource Classification (UNECE 2016) has released a report on the classification of injection projects. In addition, the Society of Petroleum Engineers will release a Geologic Storage Resources Management System (SPE 2017).

How to ensure and verify that the stored CO_2 remains in place is still a significant question from regulators and the general public. Advanced monitoring methods and well-established natural baselines are essential to ensure and document safe injection and permanent containment, and they will be a key to establishing confidence.

3.3.1. Identified technology needs

The CSLF *Technology Roadmap 2013* highlighted the risk management elements where continued research is required, and these essentially remain valid today. Significant progress has been made, as exemplified through the site characterizations, extensive monitoring programs, and risk management analyses and systems that accompanied storage applications for Quest, Gorgon, Tomakomai, Snøhvit, and Sleipner projects (renewed permits for the Norwegian projects). Also the Rotterdam Capture and Storage Demonstration Project and Goldeneye (former Peterhead) projects developed plans that met the requirements by national and European Union regulations. However, there will still be room for improvements, and local adaptations are always necessary. Mission Innovation (2018) identifies some research needs for CO_2 storage.

The following topics have been identified as technology gaps or needs for dedicated storage:[15]

- Storage
  - A unified methodology to estimate a project's CO_2 storage capacity (SPE 2017).
  - Reduced uncertainty in injectivity, which is directly linked with reduced storage risk.
  - Coordinated strategic plans for the development of transport and storage systems.
  - CO_2 storage resource portfolios and exploration and appraisal (E&A) procedures adapted to CO_2 storage to reduce uncertainties.
- Monitoring
  - New and more reliable and accurate monitoring technologies, and commercialization and cost optimization of existing monitoring technologies and techniques to support the risk management of storage.
  - Online/real-time monitoring over large areas, which will reduce operational costs and risks, including the challenge of handling large volumes of data, both during and after CO_2 injection.
- Understanding of long-term reservoir behavior
  - Models for improved understanding of fundamental reservoir and overburden processes, including integrating hydrodynamic, thermal, mechanical, and chemical processes.
  - Improved and fit-for-purpose well and reservoir technologies and management procedures, including well integrity.
- Storage integrity

[14] See also Global Carbon Atlas (2015).

[15] ZEP (2017a) gives an extensive review of CO_2 injection and storage technologies and needs.

  - Forecasting CO_2 pressure development and related geomechanical effects to minimize risk of leakage.
  - Robust CO_2 wells that prevent migration more efficiently and cost-effectively.
  - Well integrity and plug and abandon strategies for existing wells within CO_2 storage.
  - Increasing knowledge on sealing capacity of caprocks.
  - Mitigation/remediation measures.
- Interface with other areas
  - Identification of where CO_2 storage conflicts with/impacts on other uses and/or resource extraction and inclusion in resource management plans (for example, oil and gas production, marine and maritime industry, and production of drinkable water).
  - Assessments of the suitability of existing oil and gas facilities to be reused or repurposed.
  - Understanding of the effects of impurities in the CO_2 stream, including their phase behavior, on the capacity and integrity of the CO_2 storage site, with emphasis on well facilities (overlaps with CO_2 transport).
- Storage closure, post-injection monitoring, and liability transfer
  - Experience with closure and post-closure procedures for CO_2 storage projects (must wait until there are injection projects that close down).
  - Subsea CO_2 pipelines and legal aspects concerning national sovereignty and neighboring territories.
  - Strategies for taking closure into account when designing wells and dialogue with regulators to establish regulations similar to petroleum regulations.
  - Procedures for securing and closure of CO_2 storage, and post-closure monitoring.
  - Procedures for transferring liability.

3.3.2. Recommendations for CO_2 storage

Towards 2020:

Governments and industry should work together to:

On large-scale CO_2 storage

- Identify, characterize, and qualify CO_2 storage sites for large-scale systems.
- Maintain momentum for the Large-Scale Saline Storage Project Network, which was announced at the sixth CSLF Ministerial Meeting in Riyadh, Saudi Arabia, in November 2015, and which was proposed to leverage international saline storage projects that can share best practices, operational experience, and lessons learned to advance CCS deployment.
- Accelerate learning and technology development by sharing subsurface, well, and other relevant data and knowledge; for example, in initiatives such as the CO_2 Storage Data Consortium, an open, international network developing a common platform for sharing data sets from pioneering CO_2 storage projects.
- Fund RD&D activities to close technology gaps and validate the methods/technologies in case studies to accelerate the pace of CCS deployment.
- Facilitate synergies with other technologies; for example, geothermal and other relevant renewables.
- Facilitate research into the interface between transport and storage.
- Undertake regional appraisal programs with dynamic calibration and matched source-sink scenario analysis.
- Identify the sites for CO_2 storage that are most likely to work, including in developing nations.
- Improve CCS narratives around CO_2 storage, costs, and CO_2 containment risks.
- Increase public communication on CO_2 storage projects to improve the communication and dissemination of this technology and to increase knowledge and acceptance with the general public—to gain a social license to operate.

On monitoring and mitigation/remediation

- Fund activities that continue to drive down costs for existing monitoring technologies and techniques, and the development, demonstration, and validation of new measuring and monitoring techniques and sensors, onshore and offshore. This includes for leakage in terms of anomaly detection, attribution, and leakage quantification.
- Fund development and demonstration of monitoring strategies to optimize monitoring and make monitoring more cost-efficient for large-scale projects.
- Fund development and verification of mitigation and remediation methods and corrective actions for leakage, including well leakage, and test in small-scale, controlled settings.
- Identify minimum requirements/objectives for monitoring and verification (M&V) programs, both onshore and offshore, to inform fit-for-purpose legislation and regulations.

On understanding the storage reservoirs

- Further advance and utilize simulation tools, with a focus on multiphase flow algorithms and coupling of fluid flow to geochemical and geomechanical models.
- Develop and agree on consistent methods for determining CO_2 storage capacity (dynamic) reserves at various scales (as opposed to storage resources), at various levels of project maturity, and with a global distribution of this capacity.
- Further improve dynamic CO_2 capacity assessment (e.g., Smith 2017).
- Further improve on well material (steel and cement) technologies to reduce cost and risk (such as corrosion).
- Enhance the ability to more precisely predict storage efficiency by using experience from successful injections (e.g., Sleipner and Snøhvit) and knowledge on geological complexity to improve models on reservoir injectivity and plume migration.
- Enable safe injection of large amounts of CO_2 by advancing reservoir models with respect to predicting pressure buildup, and avoid hydraulic fracturing.
- Recommend workflow for caprock and fault integrity studies in CO_2 storage sites, as well as measurements and geochemical modeling of sealing capacity.
- Develop a cost model that will help improve CO_2 storage assessments.

Towards 2025:

Governments and industry should work together to:

On large-scale CO_2 storage

- Permanently store at least 400 Mt CO_2 /year by 2025 (or have permanently captured and stored 1,800 Mt CO_2), which corresponds approximately to the 2°C Scenario.
- Facilitate exploration, characterization, and qualification of large-scale CO_2 storage sites (10–100 Mt CO_2/year) in key regions of the world, building on experience from current projects and pilots and including use of existing oil and gas infrastructure.
- Facilitate qualification of 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, linked to clusters of CO_2 transport systems.
- Ensure that all CSLF member countries have national storage assessments publicly available.
- Continue the development and execution of E&A portfolio programs in key potential storage basins.
- Develop robust conceptual workflow to assure regulators that site characterization meets international leading practice.

On monitoring and mitigation/remediation

- Reduce M&V overall costs by 25% in average from 2016 levels.

Towards 2035:

Governments and industry should work together to:

On large-scale CO_2 storage

- Permanently store at least 2,400 Mt CO_2/year by 2035 (or have permanently captured and stored 16,000 Mt CO_2), which corresponds approximately to the 2°C Scenario.

On monitoring and mitigation/remediation

- Reduce M&V overall costs by 40% in average from 2016 levels.

3.4. CO_2 utilization, including enhanced hydrocarbon recovery

CO_2-EOR is the most widely used form of CCUS, with more than 120 operations, mainly onshore in North America. In 2015, over 68 million metric tonnes of CO_2 were injected in depleted oil fields in the United States for EOR, transported in a 7,600 km pipeline system (DOE NETL 2015; GCCSI 2016a), with most of the CO_2 coming from natural sources. A milestone in CO_2 capture for EOR was reached in January 2017, when the Petra Nova project in Texas started injection of 1.4 Mt CO_2/year captured from a power plant.

Canada has been injecting sour gas, a mixture of CO_2 and hydrogen sulfide, for decades as a necessary process associated with natural gas processing. In certain circumstances, the acid gas injection is in association with enhanced recovery such as the Zama field (Smith et al. 2009). Brazil is currently injecting CO_2 for EOR at the offshore fields Lula and Sapinhoá. Many other countries, including the United Kingdom, Japan (for offshore CO_2-EOR in Vietnam), Malaysia, China, the United States, Indonesia, and Norway, are working or have worked to characterize the opportunities for offshore CO_2-EOR. Other specific applications of CO_2 for 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 increase oil/gas recovery. However, these other applications are processes still being developed or tested in pilot-scale tests (CSLF 2012, 2013a); for example, the K12B site off the shore of the Netherlands has been evaluated for EGR (TNO, n.d.).

Other potential CCUS options that may lead to secure long-term storage are the use of CO_2 as the heat-transfer agent in geothermal energy systems, enhanced water recovery (EWR), carbonate mineralization, concrete curing, and bauxite residue. Mixing CO_2 with bauxite residue (red mud) has been demonstrated in Australia (GCCSI 2011). EWR is being demonstrated in China and has the opportunity to provide produced waters for other arid regions of the world. EWR has the ancillary benefit of optimizing storage capacity and mitigating pressure differences in the storage formations (Li et al. 2015).

There are several forms of CO_2 reuse, or CCU, already in use or being explored, including urea production, ethylene oxide production, ethanol production, utilization in greenhouses, conversion to polymers, methanol and formic acid production, production of bioplastics, and the cultivation of algae as a pathway to bioenergy animal feed, as well as other products. These will not lead to permanent storage but may contribute to reduced CO_2 emissions; for example, if the captured CO_2 replaces new, fresh hydrocarbons as source for carbon. 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. These options could lead to a reduction in capture costs and transport optimization and learnings.

It must be noted that for some countries, such as China (Administrative Center for China's Agenda 21 2015), CCU may provide a potential for CO_2 reduction and early opportunities to catalyze the development of CCS. Its strategic importance lies not only in offsetting the extra cost incurred in the CO_2 capture process, but also in providing a technical, policy, and legal basis and valuable engineering experience for the demonstration and promotion of CCS. More importantly, it offers a feasible strategic choice that can help ensure energy security, break regional development bottlenecks, and promote the incubation of low-carbon industries. Finally, the public's opinion of CCS as a whole may become more positive when utilization options are part of the portfolio.

For many of the CCUS and, in particular, CCU options, the total amount of CO_2 that can be permanently stored is, for all practical and economic purposes, limited (Mac Dowell et al. 2017). CO_2-EOR has the largest potential of the various CO_2 utilization options described, and it 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; the CO_2-EOR Project at the Bell Creek field in Montana; the CO_2-EOR project at Cranfield site in Mississippi; and the Farnsworth, Texas, project have performed extensive monitoring and verification of CO_2 stored in EOR operations.

Other utilization options appear to have limited potential for reducing global warming. It is important to perform life cycle assessments of the processes to secure that there are no unintended additional CO_2 emissions (Mac Dowell et al. 2017). It will be several years before these sites close down.

The lack of scalability and the economic challenges are significant barriers to the deployment of CO_2 utilization technologies in the near and long term (NCC 2016). However, in some countries utilization provides early opportunities to catalyze the implementation of CCS. In this way, the CO_2 utilization pathways can form niche markets and make a contribution to paving the way for commercial CCS. 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.[16]

3.4.1. Identified technology needs

There are technical and policy reasons to further examine the challenges of the utilization of CO_2. Recent reviews of utilization[17] point to several possible topics requiring RD&D, including the following:

- Improving the understanding of how to increase and prove the permanent storage of CO_2 in CO_2-EOR operations. CSLF (2013b) 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 the availability of high-quality CO_2 at an economic cost and in appropriate volumes; infrastructure for transporting CO_2 to oil fields; and legal, regulatory, and long-term liability must be addressed.
- Make offshore CO_2-EOR economic, including the following (CSLF 2017b):
  - Making sufficient CO_2 available; e.g., by building transport infrastructure that connects sources with reservoirs.
  - Supporting RD&D to develop and qualify new technologies.
  - Developing business models for offshore CO_2-EOR.
  - Improving volumetric sweep. Due to different well configuration in offshore fields compared with onshore EOR, alternative methods for are needed. Optimal well placement and mobility controls of CO_2 are instrumental for success.
  - Expanding experience from offshore EOR needs beyond the Lula project in Brazil.
  - Proving offshore CO_2-EOR economically viable.
- 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 and animal feed to offset primary fuel consumption and decrease agricultural cultivation practices, which might have a large CO_2 footprint.
- Improving and extending the utilization of CO_2 in greenhouses to increase the biological processes for photosynthesis, investigating marine algae cultivation for wide-scale biomass

[16] Recent reviews of utilization of CO_2 include SEAB (2016), DOE (2016), NCC (2016), CSLF (2012, 2013a), Administrative Center for China's Agenda 21 (2015), GCCSI (2011), ADEME (2010), Styring (2011), Dijkstra (2012), Tomski (2012), Markewitz et al. (2012), and ZEP (2016b). In April 2013, the *Journal of CO_2 Utilization* was launched, providing a multidisciplinary platform for the exchange of novel research in the field of CO_2 reuse pathways.

[17] See NCC (2016), CSLF (2012, 2013a), Administrative Center for China's Agenda 21 (2015), GCCSI (2011), ZEP (2016b), Styring (2011), and Mission Innovation (2018).

production, and engineering the rhizosphere to increase carbon sequestration and biomass production.

- Developing processes that enable synthetic transformations of CO_2 to fuels or chemical products, based on thermo-, electro- or photochemical processes, including catalysts made from inexpensive elements and new materials using advanced manufacturing techniques that enable large-scale processes for conversion of CO_2 directly to fuels or other products.
- Perform life cycle analysis for a range of utilization options, with the aim to learn the total carbon footprint.

3.4.2. Recommendations for CO_2 utilization

Towards 2020:

Governments and industry should work together to:

- Resolve regulatory and technical challenges for the transition from CO_2-EOR operations to CO_2 storage operations. There may be value in experiences from reporting requirements for CO_2 operations that are claiming credits under the 45Q tax credit in the United States. [18]
- 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.
- Support research and development pathways for the development of novel catalysts using abundant materials and advanced manufacturing techniques to produce nanocatalysts to bring down costs.
- Support RD&D on subsea separation and improved mobility control.
- Map opportunities, conduct technology readiness assessments, and resolve main barriers for the implementation of the CO_2 utilization family of technologies, including benchmarked life cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 reuse pathway and the energy requirement of each technology using technological modeling.

Towards 2025

Governments and industry should work together to:

- Promote more offshore CO_2-EOR pilot projects as part of deployment of large-scale CO_2 storage, as CO_2 becomes available in amounts and during time windows relevant for EOR.

[18] This refers to § 45Q of the US Internal Revenue Code, which allows for tax credits of $20 per metric tonne of qualified carbon dioxide stored and $10 per metric tonne used for EOR, captured by the taxpayer at a qualified facility. As of September 2017, there were proposals in the US Congress to increase these credits.

4. Summary

Carbon capture and storage, or CCS, will be required for nations to meet their Paris Agreement targets. Experience has shown that CCS prevents significant volumes of CO_2 from the power and industrial sectors from entering the atmosphere.

This updated Carbon Sequestration Leadership Forum technology roadmap highlights advances in capturing, utilizing, and storing CO_2 since the 2013 roadmap was issued, and it provides the nations of the world with a powerful and strategic way forward to achieve an orderly and timely transition to a lower-emissions future.

Since the last update of the technology roadmap in 2013, there have been advances and positive developments in CCS, although at a lower rate than is necessary to achieve earlier objectives. New commercial large-scale integrated projects as well as demonstration-scale projects have commenced operation both in the power and industrial sectors, and enabling legislation has been enacted in some jurisdictions. This technology roadmap has been updated in light of the Paris Agreement. In particular, the this roadmap highlights the need for CCS mitigation in industries other than the power industry and the potential of achieving negative CO_2 emissions using a combination of bioenergy and CCS. The opportunity for reducing costs by harnessing the economies of scale that can be delivered through developing industrial clusters, and CO_2 transport and storage hubs, is also highlighted.

Deployment of CCS at scale is not possible without supportive policy settings, long-term political commitment, public acceptance, and the appropriate financial support for early and long-term CCS deployment. Already, much work has been done on building fit-for-purpose regulatory frameworks to provide regulatory certainty to operators and to build confidence in communities that the process is safe.

This technology roadmap demonstrates that CCS has been successfully applied in the power industry, the gas processing industry, refineries, cement and steel production, waste-to-energy, industries using biomass as raw material, and for enhanced oil recovery. This roadmap also highlights that the implementation is well behind the trajectory to reach the Paris Agreement goal of being significantly below a 2°C temperature rise.

This roadmap sets new time horizons for medium- and long-term recommendations, with targets shifted to 2025 and 2035. This is more incisive than the previous version, as the CSLF recognizes that implementation needs to be stepped up.

5. Priority Actions Recommended for Implementation by Policymakers

Based on the findings in this report, governments and industries should partner on CCS to contribute to the Paris Agreement target of limiting the temperature increase from anthropogenic CO_2 emissions to 2°C by implementing sufficient large-scale projects in the power and industry sectors to achieve the following:[19]

- Long-term isolation from the atmosphere of at least 400 Mt CO_2 per year by 2025 (or permanent capture and storage of 1,800 Mt CO_2).
- Long-term isolation from the atmosphere of at least 2,400 Mt CO_2 per year by 2035 (or permanent capture and storage of 16,000 Mt CO_2).

This may be achieved through the following actions:

- Demonstrating the value proposition of CCS as a key technology to reduce CO_2 emissions across various sectors of the economy while providing other societal benefits (energy security; access; and additional environmental benefits, such as air pollution reduction, grid stability, and jobs preservation and creation).
- Developing and implementing policy frameworks that incentivize investments in CCS, including an equitable level of consideration, recognition, and support for CCS on similar entry terms as other low-carbon technologies, and reduce commercial risks.
- Creating an enabling market environment and innovative business models for CCS support.
- Implementing fit-for-purpose and comprehensive legal and regulatory frameworks for CCS, also on a regional scale (e.g., the London Protocol to provide for offshore cross-border movement of CO_2).
- Encouraging strategic power and industrial CO_2 capture clusters, collection hubs, and CO_2 transportation and storage infrastructures, including early mapping matching sources to sinks and identification and characterization of potential storage sites.
- Engaging in substantive CCS public outreach and education, aimed at building trust, reducing and tackling misconceptions, supporting educators as well as community proponents of CCS projects, and improving communication.
- Promoting the exchange of design, construction, and operational data; lessons learned; and best practices from large-scale projects.
- Investing deeply in RD&D for novel and emerging technologies (at the subsystem level) along the whole CCS chain to drive down costs, including synergies between CCS and renewables (e.g., geothermal).
- Funding the appraisal of storage opportunities and conducting technology readiness assessments in developing countries.
- Mapping opportunities, conducting technology readiness assessments, and resolving main barriers to the implementation of the CO_2 utilization family of technologies, including life cycle assessments and CO_2 and energy balances.

[19] The targets correspond approximately to the International Energy Agency's 2°C Scenario.

6. Follow-Up Plans

The CSLF should continue to be a platform for an international coordinated effort to commercialize CCS technology working with, among others, the IEA, the GCCSI, and the IEA Greenhouse Gas R&D Programme.

The CSLF should continue to monitor progress in light of the identified priority actions, report the findings at Ministerial meetings, and suggest adjustments and updates of the technology roadmap. It is recommended that the CSLF, through its Projects Interaction and Review Team (PIRT), monitor progress in CCS made 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, including collaboration partners.
- Prepare a simple reporting template that highlights the progress made in relation to the priority actions.
- Report annually to the CSLF Technical Group
- Report biennially, or as required, to the CSLF Ministerial Meetings.

The PIRT should continue to have the responsibility for future updates of the CSLF technology roadmap.

7. Acknowledgements

This technology roadmap was prepared for the CSLF Technical Group by an editorial committee under the auspices of the CSLF Projects Interaction and Review Team. The committee was chaired by Andrew Barrett, Australia, and had members from the United Kingdom (Brian Allison), Canada (Eddy Chui), South Africa (Tony Surridge), the United States (John Litynski), The International Energy Agency Greenhouse Gas R&D Programme (Tim Dixon), and Norway (Lars Ingolf Eide). The CSLF Secretariat (Richard Lynch) and the CSLF Technical Group Chair Åse Slagtern (Norway) have also taken active part in the discussions. The first draft of the technology roadmap was sent to a large number of international experts, and the following individuals contributed comments and input:

Norway: Philip Ringrose, Sveinung Hagen, Jørg Aarnes, Jens Hetland, Arvid Nøttvedt, Grethe Tangen, Mario Ditaranto, Svein Gunnar Bekken, Jørild Svalestuen, Svend Tollak Munkejord, Arne Dugstad, Hans Aksel Haugen, Partow Partel Henriksen, John Kristian Økland, and Tore Andreas Torp

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Australia: Paul Feron

Japan: Takayuki Higahsii

Global Carbon Capture and Storage Institute

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Several CSLF Technical Group delegates, as well as observers from the International Energy Agency and Global Carbon Capture and Storage Institute, took supplied corrections and suggestions for improvement in the next-to-final draft.

Annex A. Abbreviations and Acronyms

$/t$CO_2$	dollars per tonne of carbon dioxide
2DS	2°C Scenario
B2DS	Beyond 2°C Scenario
CSLF	Carbon Sequestration Leadership Forum
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCUS	carbon capture, utilization, and storage
CDM	Clean Development Mechanism
CO_2	carbon dioxide
CO_2-EOR	carbon dioxide-enhanced oil recovery
DOE	US Department of Energy
ECBM	enhanced coal bed methane production
E&A	exploration and appraisal
EGHR	enhanced gas hydrate recovery
EGR	enhanced gas recovery
EOR	enhanced oil recovery
EWR	enhanced water recovery
GCCSI	Global Carbon Capture and Storage Institute
H_2	hydrogen
IEA	International Energy Agency
ISO	International Organization for Standardization
km	kilometer
M&V	monitoring and verification
MPE	Norwegian Ministry of Petroleum and Energy
MW	megawatts (10^6 watts)
Mt	megatonnes (10^6 tonnes)
OECD	Organisation for Economic Co-operation and Development
PIRT	Projects Interaction and Review Team
ppm	parts per million
RD&D	research, development and demonstration
RTS	Reference Technology Scenario
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants

Annex B. Summary of Technical Recommendations

Towards 2020:

Governments and industry should work together to:

On capture

- Reduce the avoided carbon cost (or capture cost) in dollars per tonne of CO_2 ($/t$CO_2$) of currently available commercial CO_2 capture technologies for power and industry by at least 30%, while at the same time minimizing environmental impacts.
- Establish a network for knowledge sharing among full-scale facilities (e.g., by expanding the existing International Test Centre Network to share knowledge and experiences and increase understanding of the scale-up challenge).
- Resolve issues mentioned in section 3.1.2 regarding industrial CO_2 capture and bio-CCS and further develop technologies for applications and implementation in pilot plants and demonstrations.
- Increase possibilities for testing at the large pilot and demonstration scale by facilitating planning and construction of more test facilities for technologies other than solvent-based technologies.
- Fund and encourage RD&D activities for new and promising capture technologies.
- Increase activities on large-scale production of hydrogen with CCS, with the aim to develop this as a serious option in the 2025–2030 time frame.

On transport and infrastructure

- Acquire necessary data for impurities in CO_2 streams and understand the effects on pipeline materials.
- Establish and validate models that include effects as above.
- Further develop safety measures for large-scale CO_2 pipelines, including validation of dispersion models for impact assessment of incidents pursuant to leakage of CO_2 from the transport system.
- Qualify pipeline materials for use in CO_2 pipes and injection tubing when the CO_2 contains impurities.
- Optimize and qualify systems for ship transport, in particular direct offshore unloading of CO_2 to a well.
- Map the competing demands for steel and secure the manufacturing capacity for the required pipe volumes and other transport items.
- Develop systems for metering and monitoring CO_2 supplied from multiple sources with varying purity and composition that feed into a common collection and distribution system.
- Identify business cases for transportation and storage companies.
- Design and initiate large-scale CO_2 hubs that integrate capture, transport, and storage, including matching of sources and sinks.
- Develop commercial models for industrial and power CCS chains.

On storage

- Identify, characterize, and qualify CO_2 storage sites for large-scale systems.
- Maintain momentum for the Large-Scale Saline Storage Project Network, which was announced at the sixth CSLF Ministerial Meeting in Riyadh, Saudi Arabia, in November 2015, and which was proposed to leverage international saline storage projects that can share best practices, operational experience, and lessons learned to advance CCS deployment.
- Accelerate learning and technology development by sharing subsurface, well, and other relevant data and knowledge; for example, in initiatives such as the CO_2 Storage Data Consortium, an open, international network developing a common platform for sharing data sets from pioneering CO_2 storage projects.

- Fund RD&D activities to close technology gaps and validate the methods/technologies in case studies to accelerate the pace of CCS deployment.
- Facilitate synergies with other technologies; for example, geothermal and other relevant renewables.
- Facilitate research into the interface between transport and storage.
- Undertake regional appraisal programs with dynamic calibration and matched source-sink scenario analysis.
- Identify the sites for CO_2 storage that are most likely to work, including in developing nations.
- Improve CCS narratives around CO_2 storage, costs, and CO_2 containment risks.
- Increase public communication on CO_2 storage projects to improve the communication and dissemination of this technology and to increase knowledge and acceptance with the general public—to gain a social license to operate
- Fund activities that continue to drive down costs for existing monitoring technologies and techniques, and the development, demonstration, and validation of new measuring and monitoring techniques and sensors, onshore and offshore. This includes for leakage in terms of anomaly detection, attribution, and leakage quantification.
- Fund development and demonstration of monitoring strategies to optimize monitoring and make monitoring more cost-efficient for large-scale projects.
- Fund development and verification of mitigation and remediation methods and corrective actions for leakage, including well leakage, and test in small-scale, controlled settings.
- Identify minimum requirements/objectives for monitoring and verification (M&V) programs, both onshore and offshore, to inform fit-for-purpose legislation and regulations.
- Further advance and utilize simulation tools, with a focus on multiphase flow algorithms and coupling of fluid flow to geochemical and geomechanical models.
- Develop and agree on consistent methods for determining CO_2 storage capacity (dynamic) reserves at various scales (as opposed to storage resources), at various levels of project maturity, and with a global distribution of this capacity.
- Further improve dynamic CO_2 capacity assessment (e.g., Smith 2017).
- Further improve on well material (steel and cement) technologies to reduce cost and risk (such as corrosion).
- Enhance the ability to more precisely predict storage efficiency by using experience from successful injections (e.g., Sleipner and Snøhvit) and knowledge on geological complexity to improve models on reservoir injectivity and plume migration.
- Enable safe injection of large amounts of CO_2 by advancing reservoir models with respect to predicting pressure buildup, and avoid hydraulic fracturing.
- Recommend workflow for caprock and fault integrity studies in CO_2 storage sites, as well as measurements and geochemical modeling of sealing capacity.
- Develop a cost model that will help improve the CO_2 storage assessments.

Utilization

- Resolve regulatory and technical challenges for the transition from CO_2-EOR operations to CO_2 storage operations. There may be value in experiences from reporting requirements for CO_2 operations that are claiming credits under the 45Q[20] tax credit in the United States.
- 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.
- Support research and development pathways for the development of novel catalysts using abundant materials and advanced manufacturing techniques to produce nanocatalysts to bring down costs.
- Support RD&D on subsea separation and improved mobility control.
- Map opportunities, conduct technology readiness assessments, and resolve main barriers for the implementation of the CO_2 utilization family of technologies including benchmarked life cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 reuse pathway and the energy requirement of each technology using technological modeling.

Towards 2025:

Governments and industry should work together to:

On capture

- Fund and facilitate cross-border RD&D cooperation to bring to demonstration CO_2 capture technologies for power generation and industrial applications that have avoided cost in $/t$CO_2$ (or capture cost) at least 40% below that of 2016 commercial technologies, while at the same time minimizing environmental impacts.
- Fund promising CO_2 capture technology ideas to be tested and verified at pilot scale (megawatt range) and/or separating 0.01–0.1 Mt CO_2/year.

On transport and infrastructure

- Implement the first large-scale (i.e., >10 Mt CO_2/year aggregate throughput) CCS chains in power, industrial, and bio-CCS. These should be focused in industrial regions that have the potential to share infrastructure, rather than focusing on individual projects.
- Implement initial shared infrastructure for a limited number of plants within industrial clusters. This should recognize that in the initial phases, volumes within these clusters may be less than one million tonnes per annum, but that expansion from this initial start will occur.

On storage

- Facilitate exploration, characterization, and qualification of large-scale CO_2 storage sites (10–100 million tons CO_2 per year) in key regions of the world, building on experience from current projects and pilots and including use of existing oil and gas infrastructure.
- Facilitate qualification of 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, linked to clusters of CO_2 transport systems.
- Ensure that all CSLF member countries have national storage assessments publicly available,
- Continue the development and execution of E&A portfolio programs in key potential storage basins.
- Develop robust conceptual workflow to assure regulators that site characterization meets international leading practice.

[20] Refers to § 45Q of the US Internal Revenue Code, which allows for tax credits of $20 per metric tonne of qualified carbon dioxide stored and $10 per metric tonne used for EOR, captured by the taxpayer at a qualified facility. As of September 2017, there are proposals in the US Congress to increase these credits.

- Reduce monitoring and verification (M&V) overall costs by 25% in average from 2016 levels.

On utilization

- Promote more offshore CO_2-EOR pilot projects as part of deployment of large-scale CO_2 storage, as CO_2 becomes available in amounts and during time windows relevant for EOR.

Towards 2035:

Governments and industry should work together to:

On capture

- Encourage and facilitate cross-border RD&D cooperation to bring to demonstration CO_2 capture technologies for power generation and industrial applications that capture 100% (or very close to 100%) of the CO_2 and at the same time achieve 50% reduction of avoided carbon cost in \$/tCO_2 (or capture cost) compared to 2016 commercial technologies, while minimizing environmental impacts.
- Gain experience in the integration of power plants with CCS into electricity grids that utilize renewable energy sources, seeking to develop optimal hybrid concepts with zero or negative emissions.

On transport and infrastructure

- Continue progressive rollout and expansion of full-scale CCS chains and clusters in power, industrial, and bio-CCS. This includes large-scale CO_2 transport networks that integrate CO_2 capture, transport, and storage, including matching of sources and sinks.

On storage

- Reduce M&V costs by 40% from 2015 levels.

Annex C. References

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