Meeting Documents Book

carbon sequestration leadership forum

CSLF

Annual Meeting
October 15–18, 2018
Melbourne, Victoria, Australia

Carbon Sequestration Leadership Forum

www.cslforum.org

2018 CSLF ANNUAL MEETING DOCUMENTS BOOK

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Carbon Sequestration Leadership Forum

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2018 CSLF Annual Meeting

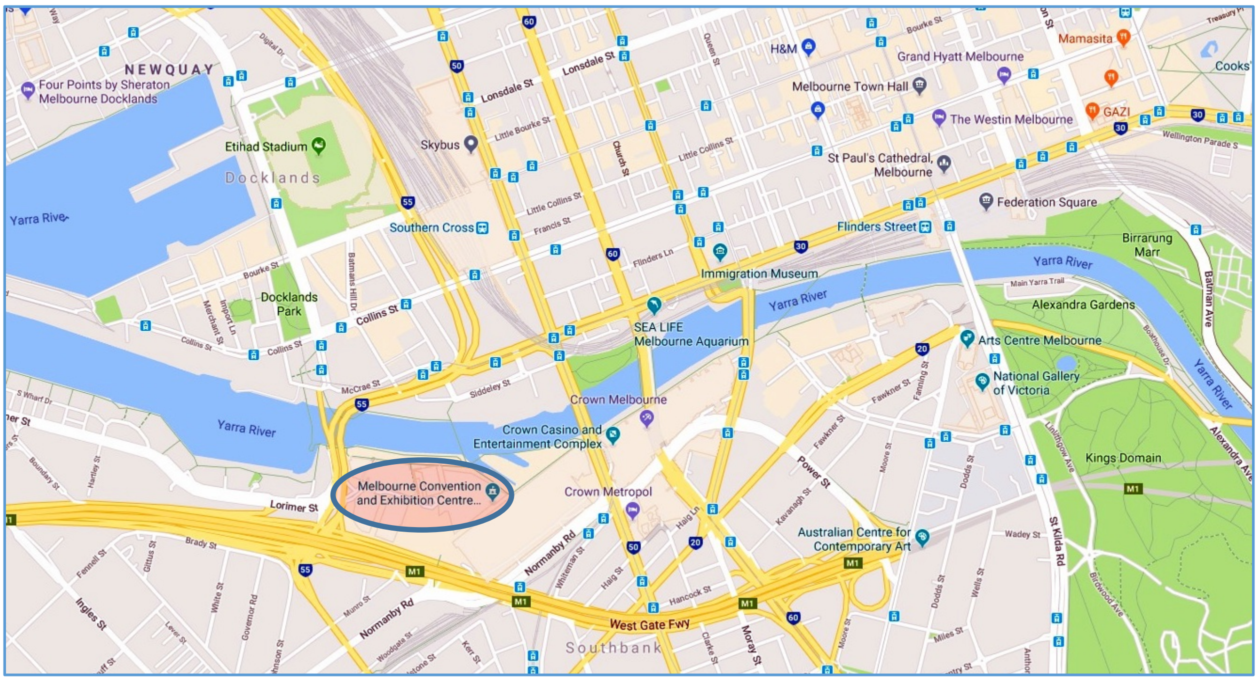
Melbourne, Victoria, Australia

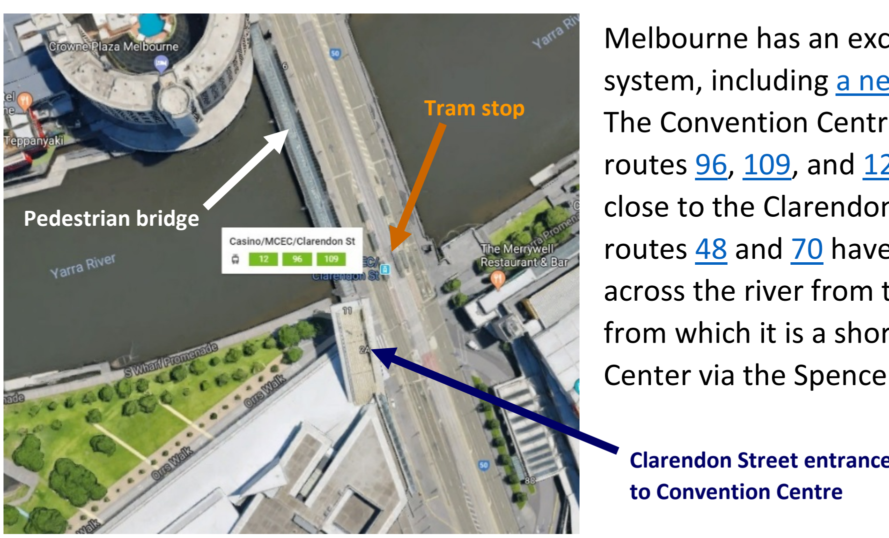
	Monday October 15	Tuesday October 16	Wednesday October 17 Melbourne Convention and Exhibition Centre Room 219	Thursday October 18 Melbourne Convention and Exhibition Centre Room 219
Morning	Bus departs for Otway Project field trip Departure time approx. 10:00am	CSLF PIRT Meeting Lady Bay Resort, Warrnambool 9:30-11:15am	CSLF Technical Group Meeting Registration 8:30am Meeting begins 9:00am	CSLF Policy Group Meeting Registration 8:30am Meeting begins 9:00am
Afternoon	Arrival at Warrnambool Arrival time TBA *(see Meeting Venue Information document for Warrnambool hotel options)*	Otway Project site visit 12:30-3:00pm Bus returns to Melbourne Arrival time approx. 7:00pm	CSLF Technical Group Meeting (continues) Meeting ends approx. 5:30pm	CSLF Policy Group Meeting (continues) Meeting ends TBA
Evening			Dinner at Half Acre Restaurant in Melbourne 6:30-9:00pm	

Meeting Venue Information

The 2018 CSLF Technical Group Meeting and Policy Group Meeting will take place on October 17 and October 18, respectively, in Melbourne, Australia at the **Melbourne Convention and Exhibition Centre**, located at the south bank of the Yarra River southwest of the Central Business District. For those arriving Melbourne by air, the Melbourne International Airport is located approx. 20 kilometers to the north-northwest of the city. In addition to taxis, there is also an express bus service into the city.

Melbourne Convention and Exhibition Centre

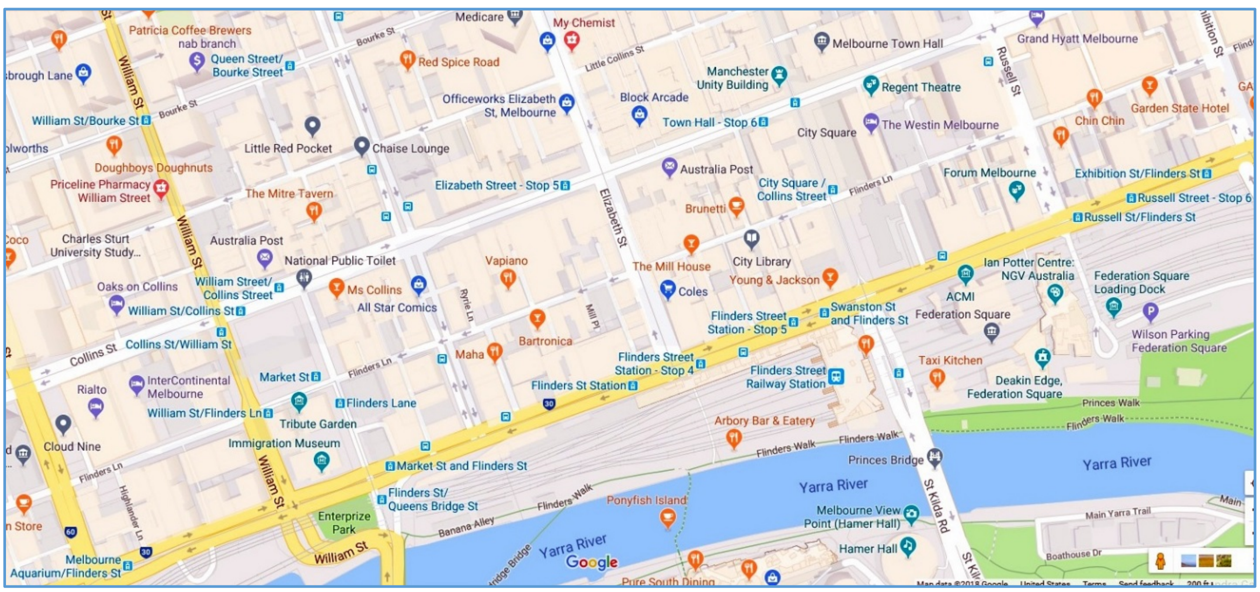




Melbourne has an excellent public transportation system, including a network of surface trams. The Convention Centre is accessible via Tram routes 96, 109, and 12 whose stops are relatively close to the Clarendon Street entrance. Tram routes 48 and 70 have stops on Flinders Street, across the river from the Convention Centre, from which it is a short walk to the Convention Center via the Spencer Street pedestrian bridge.

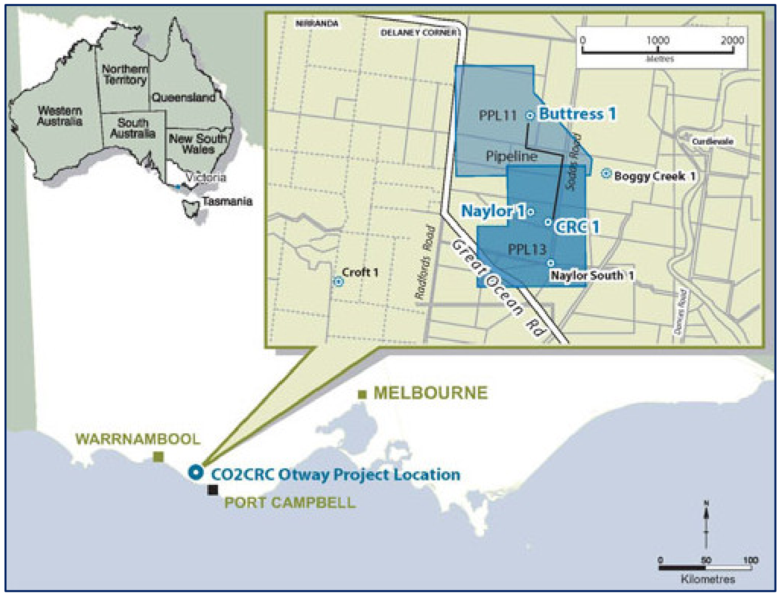
Please note that there is no reserved hotel room block for this meeting. However, there are many good hotel options, as the following maps indicate:

vicinity of Melbourne Convention and Exhibition Centre



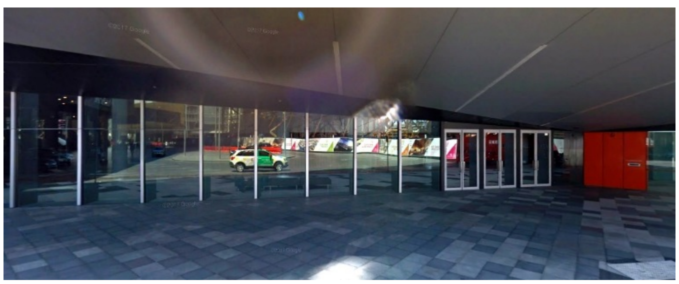
southeast corner of Melbourne's Central Business District

PIRT meeting and Site Visit to Otway Project



The CSLF Projects Interaction and Review Team (PIRT) will meet on Tuesday, October 16, as part of a field trip to the CO2CRC Otway Project. The venue for the meeting is the Lady Bay Resort in Warrnambool, which is approx. 40 kilometers from the Otway Project site.

Bus transportation will be provided from Melbourne, on the morning of Monday, October 15, for this trip. (**Bus departs from Convention Centre at 10:00am.** Pick-up point is the entrance at 1 Convention Centre Place.) There will be an overnight stay in Warrnambool, with return trip back to Melbourne on the afternoon of Tuesday, October 16. (Bus returns to Convention Centre at approx. 7:00pm.) **Please note that there is no reserved hotel room block.** Site visit attendees should make their own reservations at one of the two recommended hotels in Warrnambool:



Bus pick-up point at 1 Convention Centre Place

- Lady Bay Resort (2 Pertobe Road, Warrnambool VIC 3280; Tel: +61 3 5562 1662)
- Deep Blue Hotel (Worm Bay Road, Warrnambool, VIC 3280; Tel: +61 3 5559 2000; email: reservations@thedeepblue.com.au)

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

Please note that due to safety requirements for the site visit, you will need to be wearing a long-sleeve shirt and long pants or jeans. Also, no open-toed shoes are permitted for the site visit. It is recommended that you do not wear dress shoes for the site visit, as it will include a traverse through a cow pasture.

Draft Agenda

CSLF PROJECTS INTERACTION AND REVIEW TEAM (PIRT)

Lady Bay Resort
Warrnambool, Victoria, Australia

16 October 2018

09:30-11:15

1. **Welcome and Opening Remarks** *(5 minutes)*
   Andrew Barrett, PIRT Chair, Australia
2. **Introduction of Attendees** *(5 minutes)*
   Meeting Attendees
3. **Adoption of Agenda** *(2 minutes)*
   Andrew Barrett, PIRT Chair, Australia
4. **Approval of Summary from PIRT Meeting of April 2018** *(3 minutes)*
   Andrew Barrett, PIRT Chair, Australia
5. **Report from Secretariat** *(5 minutes)*
   - Review of Previous PIRT Meeting (Venice, April 2018)
   - Summary of CSLF Recognized Projects

   Richard Lynch, CSLF Secretariat
6. **Discussion of Results and Considerations for Technology Roadmap Follow-up, Task Force Maximization and Knowledge Sharing Assessment** *(30 minutes)*
   Sallie Greenberg, United States
   PIRT Delegates
7. **Results from CSLF-recognized Projects:**
   CO2CRC Otway Project (multiple stages) *(30 minutes)*
   Max Watson, Program Manager – Storage, CO2CRC, Australia
8. **General Discussion and New Business** *(10 minutes)*
   PIRT Delegates and Meeting Attendees
9. **Action Items and Next Steps** *(5 minutes)*
   Richard Lynch, CSLF Secretariat
10. **Closing Comments / Adjourn** *(5 minutes)*
    Andrew Barrett, PIRT Chair, Australia

Draft: 09 October 2018
Prepared by CSLF Secretariat

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CSLF Technical Group Meeting

Melbourne Convention and Exhibition Centre
Room 219
Melbourne, Victoria, Australia
17 October 2018

08:30-09:00 **Meeting Registration**

09:00-10:40 **Technical Group Meeting**

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

2. **Host Country Welcome** *(7 minutes)*
   Jason Russo, Department of Industry, Innovation and Science, Australia

3. **Introduction of Delegates** *(8 minutes)*
   Delegates

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

5. **Approval of Minutes from Venice Meeting** *(3 minutes)*
   Åse Slagtern, Technical Group Chair, Norway

6. **Report from Secretariat** *(10 minutes)*
   - Highlights from April 2018 Technical Group Meeting in Venice
   - Review of Venice Meeting Outcomes

   Richard Lynch, CSLF Secretariat

7. **Update from the CO_2GeoNet Association** *(15 minutes)*
   Sergio Persoglia, Secretary General, 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)*
   Alex Zapantis, General Manager – Commercial, GCCSI

10. **Activities of CO2CRC Ltd.** *(20 minutes)*
    David Byers, CEO, CO2CRC, Australia

10:40-10:55 **Refreshment Break**
Foyer outside Meeting Room

10:55-12:30 **Continuation of Meeting**

11. **Report from Projects Interaction and Review Team** *(10 minutes)*
    Andrew Barrett, PIRT Chair, Australia

12. **Report from CCS for Industries Task Force** *(15 minutes)*
    Didier Bonijoly, Task Force Co-Chair, France

13. **Report from Improved Pore Space Utilisation Task Force** *(15 minutes)*
    Max Watson, Task Force Co-Chair, Australia
    Brian Allison, Task Force Co-Chair, United Kingdom

14. **Report from Task Force on non-EOR Utilization Options** *(15 minutes)*
    Mark Ackiewicz, Task Force Chair, United States

15. **Report on International Overview of CO_2 Utilisation Symposium** *(15 minutes)*
    Didier Bonijoly, France

16. Results from CSLF-recognized Project: Gorgon CO_2 Injection Project *(25 minutes)*
John Torkington, Manager – Climate Change Team, Chevron Australia

12:30-13:30 Lunch
Foyer outside Meeting Room

13:30-15:30 Continuation of Meeting

17. Activities of the Australia National Low Emissions Coal Research & Development (ANLEC R&D) Initiative *(20 minutes)*
Kevin Dodds, General Manager – Research, ANLEC R&D, Australia

18. Review of China Australia Geological Storage of CO_2 (CAGS) Project *(20 minutes)*
Andrew Barrett, General Manager – Energy Systems, Geoscience Australia

19. Update from CSLF-recognized Project: CarbonNet Project *(25 minutes)*
Ian Filby, CarbonNet Project Director, Victoria Department of Economic Development, Jobs, Transport and Resources, Australia

20. Update from CSLF-recognized Project: South West Hub Project *(25 minutes)*
Dominique Van Gent, Carbon Strategy Coordinator, Western Australia Department of Mines, Industry Regulation and Safety, Australia

21. Update from the Mission Innovation Carbon Capture Challenge *(15 minutes)*
Brian Allison, United Kingdom

22. Report on 3rd International Workshop on Offshore Geologic CO_2 Storage *(15 minutes)*
Tim Dixon, Programme Manager, IEAGHG

15:30-15:45 Refreshment Break
Foyer outside Meeting Room

15:55-17:35 Continuation of Meeting

23. Update on International Test Center Network *(15 minutes)*
Frank Morton, National Carbon Capture Center, United States
M. Pourkashanian, University of Sheffield, United Kingdom

24. Preview of CSLF Presentation at GHGT14 *(10 minutes)*
Lars Ingolf Eide, Norway

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

26. Possible New Technical Group Activities *(10 minutes)*
Åse Slagtern, Technical Group Chair, Norway
Delegates

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

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

29. Election of Technical Group Officers *(10 minutes)*
Delegates
Presiding: Richard Lynch, CSLF Secretariat

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

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

CSLF Policy Group Meeting

Thursday, 18 October 2018
Room 219
Melbourne Convention and Exhibition Centre
Melbourne, Victoria, Australia

Draft Agenda

08:00-08:30 Meeting Registration

08:30-10:00 CSLF Policy Group Meeting

1. **Welcome and Opening Statement** *(5 minutes)*
   Steven Winberg, CSLF Policy Group Chair, United States
2. **Host Country Welcome** *(5 minutes)*
   Jason Russo, Department of Industry, Innovation and Science, Australia
3. **Introduction of Delegates** *(5 minutes)*
   Delegates
4. **Adoption of Agenda** *(5 minutes)*
   Steven Winberg, CSLF Policy Group Chair, United States
5. **Review and Approval of Minutes from December 2017 Policy Group Meeting in Abu Dhabi** *(5 minutes)*
   Jarad Daniels, CSLF Secretariat
6. **Report from CSLF Secretariat** *(5 minutes)*
   Jarad Daniels, CSLF Secretariat
7. **Report from CSLF Stakeholders** *(10 minutes)*
   Barry Worthington, United States Energy Association
8. **International Energy Agency (IEA) CCS Unit Update** *(10 minutes)*
   Samantha McCulloch, IEA
9. **United Kingdom and IEA International CCUS Summit on 28 November 2018 in Edinburgh** *(10 minutes)*
   Brian Allison, United Kingdom
10. **IEA Greenhouse Gas R&D Programme (IEAGHG) 14th Greenhouse Gas Control Technologies (GHGT) Conference Overview** *(10 minutes)*
    Tim Dixon, IEAGHG
11. **Report from CSLF Technical Group** *(20 minutes)*
    Åse Slagtern, CSLF Technical Group Chair, Norway

10:00-10:15 Refreshment Break

10:15-13:00 Continuation of Meeting

12. **Hydrogen Energy Supply Chain Project** *(15 minutes)*
    Sarah Chapman, Department of Industry, Innovation and Science, Australia
    Yasushi Yoshino, Kawasaki Heavy Industries, Japan
13. **Report from the Communications Task Force** *(10 minutes)*
    Hamoud AlOtaibi, Task Force Chair, Saudi Arabia
14. **Report from the Capacity Building Governing Council** *(10 minutes)*
    Stig Svenningsen, Governing Council Chair, Norway
15. **Planned International Roundtable on Strengthening Collaboration on CCUS** *(10 minutes)*
    Ryozo Tanaka, Japan

16. **Clean Energy Ministerial (CEM) Carbon Capture, Utilization, and Storage (CCUS) Initiative Update** *(90 minutes)*
    Stig Svenningsen, CEM CCUS Initiative Co-Lead, Norway
    Hamoud AlOtaibi, CEM CCUS Initiative Co-Lead, Saudi Arabia
    Jarad Daniels, CEM CCUS Initiative Co-Lead, United States
17. **Future CSLF Meetings** *(5 minutes)*
    Jarad Daniels, CSLF Secretariat
18. **Open Discussion and New Business** *(5 minutes)*
    Delegates
19. **Election of Policy Group Officers** *(5 minutes)*
    Jarad Daniels, CSLF Secretariat
20. **Summary of Meeting** *(10 minutes)*
    Jarad Daniels, CSLF Secretariat
21. **Closing Remarks / Adjourn** *(5 minutes)*
    Steven Winberg, CSLF Policy Group Chair, United States

End of CSLF Policy Group Meeting

13:00-14:00	**Lunch**
14:00-17:00	**Clean Energy Ministerial (CEM) Carbon Capture, Utilization, and Storage (CCUS) Initiative Meeting**

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MEETING SUMMARY

Projects Interaction and Review Team (PIRT) Meeting
Venice, Italy
22 April 2018

Prepared by the CSLF Secretariat

LIST OF ATTENDEES

PIRT Active Members

Australia:	Andrew Barrett (Chair), Max Watson
Canada:	Eddy Chui, Mike Monea
France:	Didier Bonijoly, David Savary
Italy:	Paolo Deiana, Sergio Persoglia
Japan:	Ryozo Tanaka, Jiro Tanaka
Korea:	JaeGoo Shim, YiKyun Kwon
Netherlands:	Paul Ramsak
Norway:	Lars Ingolf Eide, Åse Slagtern (Technical Group Chair), Espen Kjærgård
Poland:	Anna Madyniak
Romania:	Sorin Anghel
United Kingdom:	Brian Allison
United States:	Mark Ackiewicz, Sallie Greenberg

Allied Organizations

IEAGHG:	James Craig
GCCSI:	John Scowcroft
CO_2GeoNet:	Marie Gastine, Rowena Stead, Ceri Vincent

CSLF Secretariat Richard Lynch

Invited Speaker

Marie Gastine, ENOS Coordinator, BRGM and CO_2GeoNet, France

Observers

Canada:	Simon O'Brien (*Shell*)
Japan:	Takashi Kamijo, Chibumi Kimura, Makoto Susaki, and Yasuhiro Tatsumi (*MHI Engineering*)
Saudi Arabia:	Pieter Smeets (*SABIC*)
United Kingdom:	Mark Crombie (*BP*) M. Pourkashanian (*University of Sheffield*)

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1. Welcome

PIRT Chairman Andrew Barrett welcomed participants to the 28th meeting of the PIRT. Mr. Barrett stated that the three major items to be taken up at this meeting were review of the ENOS Project which has nominated for CSLF recognition, an update from the PIRT working group to explore feasibility for measuring progress on recommendations from the 2017 CSLF Technology Roadmap (TRM), and an update from the working group on exploring existing and new ideas for possible future Technical Group actions. Mr. Barrett thanked Italy's Ministry of Economic Development for hosting the meeting and thanked Sergio Persoglia and the CO_2GeoNet Association for providing large amounts of organizational support on arranging the facilities and logistics for the meeting.

2. Introduction of Meeting Attendees

PIRT meeting attendees introduced themselves. In all, twelve 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 Abu Dhabi PIRT Meeting

The Meeting Summary from the December 2017 PIRT meeting in Abu Dhabi 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 of December 2017 in Abu Dhabi.

Concerning the portfolio of CSLF-recognized projects, Mr. Lynch stated that as of April 2018 there were 34 active projects and 20 completed projects spread out over five continents. For the current meeting, one new project has been proposed for CSLF recognition.

Mr. Lynch reported that there were four outcomes from the Abu Dhabi meeting:

- The PIRT recommended approval by the Technical Group for the CO2CRC Otway Project Phase 3 to be a CSLF-recognized project.
- The 2017 TRM was completed and launched.
- The PIRT's Terms of Reference (ToR) document was revised to update project recognition procedures and to make it consistent with the CSLF Charter. Mr. Lynch acknowledged the help of both Ryozo Tanaka and Max Watson in assembling all the changes into an annotated draft of the revised ToR.
- A PIRT working group was organized to explore and suggest approaches for tracking follow-up and progress on TRM recommendations.

Mr. Lynch concluded his report by stating that there was one Action Item from the previous PIRT meeting: the Secretariat was asked to produce a new version of the PIRT Terms of Reference which incorporates all agreed changes, and this has been completed.

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6. Review and Approval of Project Proposed for CSLF-Recognition: Enabling Onshore CO_2 Storage in Europe (ENOS)

Marie Gastine, representing BRGM and the CO_2GeoNet Association, gave a detailed technical presentation about the ENOS project. 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.

Outcome: After a discussion which clarified some of the details about the project, there was unanimous consensus by the PIRT to recommend approval of ENOS by the Technical Group. Project nominators are Italy (lead), Australia, Canada, France, the Netherlands, Norway, Romania, and the United Kingdom.

7. Measuring Progress on Recommendations from the 2017 TRM

Lars Ingolf Eide made a presentation that followed up on one of the outcomes from the December 2017 PIRT meeting. At that meeting there was agreement that the PIRT should find ways on how to measure progress toward carbon capture and storage (CCS) in light of current TRM recommendations and that, in the longer term, the PIRT could utilize expertise and learnings from CSLF-recognized projects as an input to future editions of the TRM. To that end, a small working group was organized to further explore the feasibility of doing this. Mr. Eide, as spokesman for the working group, stated that the intent of this activity would be to find and implement corrective actions, as much as it is possible, where progress on implementing recommendations from the TRM has been slow. The working group would monitor the status of the TRM's priority recommendations, which were presented to the 2017 Conference of CSLF Ministers in December. There are ten such recommendations, five under the Technical Group and five under the Policy Group.

Mr. Eide proposed that the working group operate under a single lead coordinator, with topics to be assigned to one or more working group members (each of whom may have to work on more than one topic). Overall there would be seven topics: one for the 2025 target for global CO_2 storage (400 megatonnes per year, or 1,800 megatonnes cumulative), one that lumps together the five recommendations under the Policy Group, and one for each of the five recommendations under the Technical Group:

- Facilitate CCS infrastructure development;
- Leverage existing large-scale projects to promote knowledge-exchange opportunities;

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- Drive costs down along the entire CCS chain through research, development and demonstration (RD&D);
- Facilitate innovative business models for CCS projects; and
- Facilitate implementation of CO_2 utilization

Mr. Eide stated that a template could be used for reporting, and the overall approach should include participation of CSLF allied organizations and other stakeholders with an interest in CCS as well as CSLF delegates. There would be annual reports from the working group, and corrective actions (where warranted) could include joint workshops / task forces / webinars with allied organizations and others. Additionally, there could be communications or other interactions with governments, industry, and other stakeholders to promote CCS and CO_2 utilization. Mr. Eide ended his presentation by stating benefits which can be achieved by this approach: an easier and new approach for identifying new task forces, increased engagement from CSLF members, closer cooperation with allied organizations and other stakeholders, and transforming the TRM into a living document to which decision makers pay attention.

Ensuing discussion confirmed that this is one of the PIRT's most important areas of interest. There was consensus that the details for moving forward in this area were not solvable at the current meeting but that the Secretariat would moderate an offline discussion for any delegates who wanted to have a role. Additionally, this item will be on the agenda for the next PIRT meeting, in October 2018, where a plan for measuring progress on 2017 TRM recommendations will be proposed.

8. Update from Working Group on Evaluating Existing and New Ideas for Possible Future Technical Group Actions

The CSLF Technical Group Chair, Åse Slagtern, made a short presentation that summarized existing Technical Group activities and possible new ones in advance of a more detailed discussion during the next day's full Technical Group Meeting. At the 2017 CSLF Mid-Year Meeting, a working group (led by Norway) had been created by the Technical Group to appraise all unaddressed items in the Action Plan from 2015, propose new topics for appraisal, and review past task force reports to see if any updates are warranted. A preference poll of working group members resulted in "Hydrogen as a Tool to Decarbonize Industries" being the highest ranked option for a new task force, which led to the formation of a new Technical Group task force on that topic.

Ms. Slagtern stated that there are currently three other active task forces: Improved Pore Space Utilization (co-chaired by Australia and the United Kingdom), Bioenergy with CCS (chaired by the United States), and CCS for Energy Intensive Industries (chaired by France). Additionally, there are twelve other possible future actions, identified by the 2015 working group, but there had not yet been any consensus to form task forces around these possible actions. There have also been seven actions which were completed between 2013 and 2017 and have resulted in task force final reports.

Ensuing discussion centered on other task force options which had achieved a high prioritization ranking from the working group, though decisions on these items would be made at the next day's full Technical Group meeting. Mark Ackiewicz suggested that the Technical group take a new look at Utilization Options for CO_2, which had been the topic of a previous task force in 2011-2013. There was additional discussion concerning the merits or forming task forces in the areas of CO_2 Capture by Mineralization, Reviewing Best Practices and Standards for Geologic Monitoring and storage, and

Global Scaling of CCS. Brian Allison inquired if any of these would qualify for a study by the IEA Greenhouse Gas R&D Programme (IEAGHG), and James Craig responded that the IEAGHG welcomed suggestions of this nature and mentioned that CSLF backing could be influential but that there was a defined process for new studies and that not all proposals resulted in studies being commissioned.

9. General Discussion and New Business

There was discussion about the PIRT's project review process. Mark Ackiewicz mentioned that there did not seem to be a formalized way for documenting any questions that might arise from review of completed submission forms for projects being nominated for CSLF recognition. Richard Lynch suggested that the Secretariat could produce a document that summarizes any questions or comments for any project being reviewed by the PIRT and that the document could be provided in advance to the project sponsor so that the questions and comments could be addressed during the project presentation at the PIRT meeting. There was consensus that this approach be adopted.

10. Adjourn

Mr. Barrett thanked the attendees for their interactive participation, expressed his appreciation to the host Italian Ministry of Economic Development, and adjourned the meeting.

Summary of Meeting Outcomes

- The PIRT has recommended approval by the Technical Group for the ENOS project to be a CSLF-recognized project.
- Measuring progress on recommendations from the 2017 TRM is one of the PIRT's most important areas of interest, and will be a centerpiece of future PIRT meetings.

Actions

- The CSLF Secretariat will set up an offline discussion for PIRT delegates to develop details for moving forward on finding ways to measure progress on recommendations from the 2017 TRM. (*Note: This was superseded by a Technical Group outcome at its meeting the next day*.)
- The CSLF Secretariat will henceforward produce a document that summarizes any questions or comments for any project being reviewed by the PIRT.

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Minutes of the Technical Group Meeting

Venice, Italy
Monday, 23 April 2018

LIST OF ATTENDEES

<u>Chair</u> Åse Slagtern (Norway)

<u>Delegates</u>

Australia:	Andrew Barrett (*Vice Chair*), Max Watson
Canada:	Eddy Chui (*Vice Chair*), Mike Monea
France:	Didier Bonijoly, David Savary, Dominique Copin
Italy:	Paulo Deiana, Sergio Persoglia
Japan:	Ryozo Tanaka, Jiro Tanaka
Korea:	JaeGoo Shim, YiKyun Kwon
Netherlands:	Paul Ramsak
Norway:	Lars Ingolf Eide, Espen Kjærgård
Poland:	Anna Madyniak
Romania:	Sorin Anghel
Saudi Arabia:	Hamoud AlOtaibi, Tidjani Niass
United Kingdom:	Brian Allison
United States:	Mark Ackiewicz, Sallie Greenberg

<u>Representatives of Allied Organizations</u>

CO_2GeoNet:	Isabelle Czernichowski-Lauriol, Rowena Stead, Ceri Vincent, Ton Wildenborg
Global CCS Institute:	John Scowcroft
IEAGHG:	James Craig

<u>CSLF Secretariat</u> Richard Lynch

<u>Invited Speakers</u>

France:	Marie Gastine (*BRGM and CO_2GeoNet*)
Italy:	Marcello Capra (*Ministry of Economic Development*)
Japan:	Takashi Kamijo (*MHI Engineering*)
Norway:	Svend Tollak Munkejord (*SINTEF Energy Research*)
United Kingdom:	Mark Crombie (*BP*)
United States:	James Sorensen (*University of North Dakota Energy and Environmental Technology Center*)

<u>Observers</u>

Canada:	Simon O'Brien (*Shell*)
Japan:	Chibumi Kimura, Makoto Susaki, and Yasuhiro Tatsumi (*MHI Engineering*)
Saudi Arabia:	Pieter Smeets (*SABIC*)
United Kingdom:	M. Pourkashanian (*University of Sheffield*)

1. Chairman's Welcome and Opening Remarks

The Chair of the Technical Group, Åse Slagtern, called the meeting to order and welcomed the delegates and observers to Venice. Ms. Slagtern mentioned that this would be a busy meeting, with presentations on many topics of interest including results from four CSLF-recognized projects plus review of one new project which has been nominated for CSLF recognition. Additionally, there would be presentations about several technology areas related to carbon capture and storage (CCS) as well as updates from 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

Marcello Capra, Senior Expert at Italy's Ministry of Economic Development, welcomed the meeting attendees to Venice. Mr. Capra stated that Italy last hosted a CSLF Technical Group meeting in 2013, in Rome, and that Italy had become a Charter Member of the CSLF at its very first meeting in 2003. The current situation in Italy is that the Italian Government has launched a new National Energy Strategy which is focused on achieving climate and energy goals in harmony with 2015 Paris Climate Conference (COP21) targets. This includes phasing out all coal-fueled power plants by the year 2025. Dr. Capra stated that in regards to CCS, Italy is a participant in several European projects including ENOS (see below), and that the feasibility of CCS for the industrial sector such as in cement production is being investigated. Dr. Capra also mentioned that the current Technical Group meeting reinforces the strategic role of international collaboration for development of new energy technologies which mutually address energy security and environmental concerns, and that the meeting presents a great opportunity for a fruitful exchange of knowledge among meeting attendees.

3. Introduction of Delegates

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

4. Adoption of Agenda

The Agenda was adopted with no changes.

5. Approval of Minutes from December 2017 Meeting in Abu Dhabi

The Minutes from the December 2017 Technical Group Meeting in Abu Dhabi were approved with no changes.

6. Report from CSLF Secretariat

Richard Lynch provided a report from the CSLF Secretariat which reviewed highlights from the December 2017 CSLF Ministerial Meeting. This was a five-day event, including a Conference of CSLF Ministers and their delegates, and also a Ministers' site visit to the Al Reyadah Carbon Capture, Utilization and Storage (CCUS) Project. Presentations from all meetings are online at the CSLF website.

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Concerning the CSLF Conference of Ministers, Mr. Lynch stated that there were many key actions identified that are needed to accelerate the acceptance and large-scale deployment of CCUS:

- Encouraging the development of regional strategies that strengthen the business case for CCUS and accelerate its deployment;
- Exploring new utilization concepts beyond CO_2 enhanced oil recovery (CO_2-EOR) that have the potential to add commercial value;
- Supporting collaborative R&D on innovative, next generation CCUS technologies with broad application to both the power and industrial sectors;
- Expanding stakeholder engagement and strengthening links with other global clean energy efforts to increase public awareness of the role of CCUS;
- Increasing global shared learnings on CCUS by disseminating best practices and lessons learned from CCUS projects; and
- Continuing to engage the public on CCUS and looking for ways to communicate effectively.

Mr. Lynch reported that there were also several other notable highlights from the meeting:

- The 2017 CSLF Technology Roadmap (TRM) was launched;
- Results from regional stakeholder surveys were documented and summarized;
- Three completed projects received CSLF Global Achievement Awards: the CANMET Energy Oxyfuel Project, the Lacq Integrated CCS Project, and the Plant Barry Integrated CCS Project; and
- The CO2CRC Otway Project Stage 3 received CSLF recognition.

Mr. Lynch concluded his presentation by reporting that the Technical Group meeting had its own set of outcomes:

- The Offshore CO_2-EOR Task Force issued its final report and has completed its activities;
- The Bioenergy with CCS (BECCS) Task Force and Improved Pore Space Utilisation Task Forces were on schedule to present their final reports at the next Technical Group meeting;
- The CCS for Energy Intensive Industries Task Force was on schedule to present a draft report at the next Technical Group meeting;
- A new Task Force on Hydrogen Production and CCS was formed (but only for preliminary "Phase 0" activities);
- A detailed proposal for a new task force on CO_2 Capture by Mineralization would be presented at the next Technical Group meeting; and
- United States delegate Sallie Greenberg was designated as the Technical Group's liaison to the ISO TC265 technical committee on CO_2 capture, transport and geologic storage.

There was ensuing discussion concerning the CSLF Global Achievement Awards. Ryozo Tanaka inquired as to the criteria for eligibility. Mr. Lynch responded that any CSLF-recognized project which has been successfully concluded is eligible for an award. Also, large-scale projects which do not have an end date are eligible for an award when they achieve a major milestone, such as in the amount of CO_2 stored.

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7. Update from the CO_2GeoNet Association

Ton Wildenborg, the President 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. Wildenborg 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. Wildenborg then provided an update on recent activities of the organization. Since the December 2017 CSLF Ministerial meeting in Abu Dhabi, the CO_2GeoNet Association has been involved in several European policy-related actions concerning CCS, including being an advisor on the European Union’s Strategic Energy Technology Plan concerning CCUS with special reference to developing and updating its storage atlas and storage appraisal. It is also helping to define the scope of the 9th European Union Framework Programme for Research and Innovation as it pertains to CCUS. CO_2GeoNet is also one of the reviewers for the second order draft of the Intergovernmental Panel on Climate Change (IPCC) Special Report on the 1.5 degrees scenario. Dr. Wildenborg concluded his presentation by stating that the CO_2GeoNet Association was pleased to accept the invitation to become a Technical Group Allied Organization, and that the Technical Group has been invited to designate a CSLF representative to the CO_2GeoNet Advisory Committee.

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

James Craig, Senior Geologist at the IEAGHG, gave a presentation about the IEAGHG 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. The focus is on CCS, and the goal of the organization is to produce information that is objective, trustworthy, and independent, while also being policy relevant but not policy prescriptive. The “flagship” activities of the IEAGHG are the technical studies and reports it publishes on all aspects of CCS (320 reports published as of April 2018), the eight international research networks about various topics related to CCS, and the biennial GHGT conferences (the next one in October 2018 in Melbourne, Australia). 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.

Dr. Craig mentioned that since 2008 the IEAGHG and CSLF Technical Group have enjoyed a mutually beneficial relationship which allows each organization to cooperatively participate in the other’s activities. This has included mutual representation of each at CSLF Technical Group and IEAGHG Executive Committee (ExCo) meetings, and also the opportunity for the Technical Group to propose studies to be undertaken by the IEAGHG. These, along with proposals from IEAGHG ExCo members, go through a selection process at semiannual ExCo meetings. So far there have been four IEAGHG studies that originated from the CSLF Technical Group, plus an additional proposed study which became the 2nd International Workshop on Offshore Geologic CO_2 Storage.

Dr. Craig concluded his presentation with a list of reports recently published, reports in progress to be published, studies underway, and studies awaiting start. Dr. Craig also briefly described IEAGHG events, including its webinar series and the upcoming GHGT conference.

9. Update from the Global CCS Institute

John Scowcroft, General Manager for Europe at the Global Carbon Capture and Storage Institute (GCCSI), gave a brief verbal update about the GCCSI. The Institute has recently reorganized on how it operates, having moved away from a regional structure toward more of a global outlook on CCS. 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. Scowcroft stated that the GCCSI, in the nine years of its existence, has brought experience, expertise, and resources to help provide its members and stakeholders impactful information which can be used for both policy making and understanding the varied technologies of CCS. In closing, Mr. Scowcroft stated that the GCCSI has at its website many tools and resources about CCS including its "Global Status of CCS" document as well as various reports and fact sheets. Mr. Scowcroft also mentioned that the GCCSI's annual Asia-Pacific CCS Forum would be held in early May, in Shanghai, China, and that there was still time to register for the event.

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

The PIRT Chair, Andrew Barrett, gave a short presentation which summarized the previous day's meeting. Mr. Barrett reported that the meeting was centered on three topics:

- The PIRT has recommended approval by the Technical Group for the Enabling Onshore CO_2 Storage in Europe (ENOS) project in becoming a CSLF-recognized project.
- There was a lively discussion on how to measure progress on recommendations from the TRM.
- There was a discussion on possible Technical Group future activities, as a lead-in to the discussion on that topic in the current Technical Group meeting

Mr. Barrett provided some additional detail about the PIRT's responsibility for measuring progress on recommendations from the TRM. A small working group had been assembled prior to the PIRT meeting and expanded during the meeting to nine PIRT delegates. The expectation is that by the time of the next PIRT meeting, in October, a procedure will have been agreed to on how to accomplish this undertaking, even though some of these recommendations pertain solely to the Policy Group. There is a very strong probability that how much progress toward addressing the TRM recommendations may influence what task forces the Technical Group may decide to form at some point in the future. This, as well as expertise and learnings from CSLF-recognized projects, could be input to the next edition of the TRM.

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11. Enabling a Low-Carbon Economy via Hydrogen and CCS (ELEGANCY)

Svend Tollak Munkejord, ELEGANCY project coordinator for SINTEF Energy Research, made a presentation about both SINTEF and the ELEGANCY project. SINTEF is an independent and non-commercial organization, headquartered in Trondheim, Norway, which conducts contract R&D projects. The Energy Research arm of SINTEF provides services both in Norway and globally which contribute toward the achievement of future sustainable energy systems, for which ELEGANCY is one possible approach.

Dr. Munkejord stated that the context behind ELEGANCY is that a low-carbon economy needs both hydrogen and CCS, so combining hydrogen production with CCS offers opportunities for synergies and value creation. To that end, ELEGANCY aims at contributing toward fast-tracking the decarbonization of the European energy system. The objectives of the project include developing and demonstrating effective CCS technologies with high industrial relevance, identifying and promoting business opportunities for industrial CCS enabled by hydrogen as a key energy carrier, validating key elements of the CCS chain in pilot- and laboratory-scale experiments, de-risking CO_2 storage from hydrogen production by providing experimental data and validated models, providing an open source techno-economic design and operation simulation tool for the full CCS chain including hydrogen as energy carrier, and assessing societal support for key elements of CCS. Dr. Munkejord stated that there would be several country-specific case studies as part of the overall work package, which would be carried out with partner organizations in those countries and will include hydrogen utilization scenarios as well as CCS evaluation. These will be inputs into developing a business case for hydrogen with CCS. The overall budget for ELEGANCY is approximately €15.6 million over the three year project duration, which began in August 2017.

12. Report from the Task Force on Hydrogen Production and CCS “Phase 0” Activities

Task force Chair Lars Ingolf Eide gave a report on the task force, which had been formed at the December 2017 Technical Group meeting in Abu Dhabi. A working group had identified “Hydrogen as a Tool to Decarbonize Industries” as a high priority item for a Technical Group task force, but given that there has been activity in this area by research organizations and industry in several CSLF member countries, the task force had been sanctioned only to gather information on what other organizations have been doing in regards to this topic.

Mr. Eide stated that the task force’s investigations covered the future outlook for hydrogen production with CCS as well as how it is presently being implemented in specific parts of the world. Overall, there is expected to be up to a ten-fold increase in hydrogen demand by the year 2050, but there is not yet an economically effective way to produce carbon-free hydrogen in the quantities that will be needed. In Canada, hydrogen production with CCS is currently being implemented in Alberta province at the Quest Project and will also be a part of the under-construction Northwest Sturgeon Project. In China, hydrogen production and CCS are components of several projects, including a coal liquefaction plant and a petroleum refinery. The European Commission is supporting the ELEGANCY project, and there is an evaluation in progress in the Netherlands for converting a natural gas-fueled power plant into a hydrogen-fueled facility with associated carbon capture. Mr. Eide stated that Japan already has a sizeable hydrogen economy including hydrogen-powered fuel cell vehicles, and a natural next step would be to incorporate CCS as a component of hydrogen production. Hydrogen with CCS is also being investigated for application in Norway and the United Kingdom, while in the United States the large-scale industrial Air Products project has been producing hydrogen with carbon capture (into a pipeline for use as CO_2-EOR) for several years. In addition to all of these, the IEAGHG has been actively investigating the techno-economic evaluation of hydrogen with CCS.

Mr. Eide reported that, in general, the task force's findings are that hydrogen production with CCS is already being implemented and there are few if any technical barriers to CO_2 capture associated with large-scale hydrogen production, but continued research, development and innovation for improved and emerging technologies for clean hydrogen production should be encouraged. Mr. Eide then stated that he did not recommend that the task force continue beyond these "Phase 0" fact finding activities because there is already much duplicative work in progress, as has been shown by the ELEGANCY presentation. The Technical Group's task force on CCS for Energy Intensive Industries can also include hydrogen production with CCS as one of its areas of interest. Mr. Eide proposed that alternatively, a workshop on hydrogen production with CCS would be useful and that such a workshop could be done in partnership with other organizations such as the IEAGHG.

During ensuing discussion, Andrew Barrett mentioned that Australia also has activities related to hydrogen with CCS with a pilot project producing hydrogen for export from the brown coal deposits in the Gippsland region of Victoria state. There was consensus that the task force not proceed beyond its now-concluded "Phase 0" activities and Mr. Eide was asked to produce a task force report that can be published at the CSLF website. Additionally, the Technical Group will coordinate with allied organizations to hold a workshop on hydrogen with CCS at a future CSLF meeting.

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

Task force Co-Chair Dominique Copin 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. Overall, cumulative CO_2 emissions from energy intensive industries are comparable in scale to those from the power generation sector. Mr. Copin reported that the task force consists of members from France's Club CO_2, with additional commitment 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.

Mr. Copin stated that relevant issues being examined 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. Task force findings are that for most energy intensive industries, a significant part of CO_2 emissions are due to the process itself and not to fossil fuel consumption. Usage of renewable energy for many industries therefore cannot be regarded as an alternative to CCS in terms of reducing CO_2 emissions from those industries. Business models for developing CCS will have to be developed by these industries, which may require support of government.

Mr. Copin concluded his presentation by stating that the task force has completed much of its work and that draft versions of most chapters in its final report have been prepared. The target is to have the final report complete in time for the 2018 CSLF Annual Meeting in October.

14. Report from the Bioenergy with CCS (BECCS) Task Force

Task force Chair Mark Ackiewicz gave a brief update on the task force, which was established at the November 2015 meeting in Riyadh and has now completed its activities. Task force members included the United States as lead, Norway, the United Kingdom, and the IEAGHG. Mr. Ackiewicz stated that the task force's final report has been completed and was included in the documents for the current meeting. The report includes an executive summary and introductory chapter as well as chapters which provide a summary of resource assessments and emissions profiles, the commercial status of BECCS technology development, and an overview of BECCS technology options and pathways.

Mr. Ackiewicz summarized task force findings. There are currently many barriers for BECCS and progress is needed in several key areas: technical, economic, resource limitations, policy / regulation, and supply chain development. There were ten recommendations:

- R&D is needed to develop and identify biomass feedstocks that require limited processing;
- Optimization is needed for biomass feedstock water use and the carbon footprint;
- Availability of biomass feedstocks should be monitored on a regional basis;
- Biomass pre-treatment processes (densification, dehydration, pelletization) need improvement;
- Technologies with lower costs and energy penalties need to be identified and developed;
- A common framework for lifecycle assessment should be developed in order to facilitate accurate accounting of the BECCS carbon footprint;
- Policy makers should be informed with respect to the benefits of BECCS market opportunities;
- There is a need to build trust with public and local communities;
- Stronger collaboration is needed between CCUS stakeholders, bioenergy, and BECCS industries; and
- There is a need to financially incentivize the double benefit of BECCS.

Mr. Ackiewicz closed his presentation by stating that the task force had concluded its activities. There was consensus by the Technical Group to disband the task force.

15. Report from the Improved Pore Space Utilisation Task Force

Task force Co-Chair 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. Dr. Watson 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. 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.

Dr. Watson stated that the task force's final report would include seven topics related to pore space utilisation: oil & gas literature review, non-technical issues related to improved pore space utilisation, pressure management, microbubble injection, CO_2 saturated water injection & geothermal energy production, compositional & temperature swing injection, and technique effectiveness. Work is complete on all topics except for the technology effectiveness section, which will be finished soon. Dr. Watson concluded his presentation by stating that the task force timeline now shows the final report being complete by August 2018 and it will be part of the documents book for the 2018 CSLF Annual Meeting in Melbourne.

16. Review and Approval of Project Proposed for CSLF-Recognition: Enabling Onshore CO_2 Storage in Europe (ENOS)
(nominated by Italy [lead], Australia, Canada, France, the Netherlands, Norway, Romania, and the United Kingdom)

Marie Gastine, representing BRGM and the CO_2GeoNet Association, gave an overview presentation about the ENOS project. 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.

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

17. Update on Mitsubishi's KM CDR Process and Experience

Takashi Kamijo, Chief Engineering Manager for CO_2-EOR Business Development at Mitsubishi Heavy Industries (MHI), gave a presentation which described MHI's amine-based Kansai Mitsubishi Carbon Dioxide Removal (KM CDR) process and its application in industry and power generation. The process utilizes a proprietary hindered amine solvent which has the benefits of low energy, low solvent degradation and negligible corrosion. The process also features a proprietary heat recovery system, a deep amine emission reduction system, and an automatic load adjustment system. There are currently 13 commercial KM CDR installations worldwide of at least 200 tonnes CO_2 capture per day, plus one installation of 1,200 tonnes CO_2 capture per day that is under construction. The largest of these is the Petra Nova Project, near Houston, Texas in the United States, which has a CO_2 capture capacity of 4,776 tonnes per day from a coal-fueled power generation unit at the W.A. Parish Generating Station. This installation is currently the world's largest power plant-based carbon capture project.

Mr. Kamijo described the KM CDR process as being commercial since 1999 with most of the installations at urea production facilities. The process has seen use with various flue gas sources (natural gas, heavy oil, and coal), and that CCUS has been the main driver for the commercial projects where it is in use. There have so far been two KM CDR Users' Conferences (the most recent in 2015 in Bahrain) where operation experiences have been shared, with lessons learned being used to improve the process. Mr. Kamijo concluded his presentation by briefly describing the ongoing effort by MHI Engineering to further improve the process. These include reducing the cost of capturing CO_2 through technical improvements which will increase efficiency and reduce solvent degradation.

18. Results from CSLF-recognized Projects: Zama Project and Fort Nelson Project

James Sorensen, Principal Geologist at the University of North Dakota's Energy and Environmental Research Center (EERC), gave a presentation about two CSLF-recognized projects located in western Canada. The Zama Acid Gas EOR, CO_2 Sequestration and Monitoring Project, located in northern Alberta province, was a pilot-scale project which utilized acid gas (approx. 70% CO_2 and 30% hydrogen sulfide) derived from natural gas extraction for enhanced oil recovery. A total of 85,000 tonnes was injected over the duration of the 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. Additional goals were to assess and quantify the uncertainties associated with existing data in order to help CO_2 storage from operational and planning standpoints, to provide insight regarding the design of the CO_2 storage scheme, and to obtain an improved estimate of the recoverable oil resource and associated storage. Mr. Sorensen stated that a key conclusion from the project was that the presence of hydrogen sulfide in the EOR gas stream can lower the minimum miscibility pressure which results in an overall improvement by lowering the cost of injection, though process modifications and specialized equipment are required to ensure safety and minimize corrosion. Additionally, two other conclusions were that so-called geologic "pinnacle reefs", such as the ones utilized by this project, are great candidates for CO_2 storage, and "sour" CO_2 can be safely and economically used for geologic storage and CO_2-EOR.

The Fort Nelson CCS Project, located in northern British Columbia province, had the objective of developing 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 feasibility study incorporated a risk-based approach to define the MVA strategy, modeling and simulation, site characterization, risk

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assessment, and development of a cost-effective MVA plan. Mr. Sorensen stated that there was a 50-year injection scenario with three injection wells and up to 2.5 million tonnes injection per year of CO_2 captured from a nearby gas-processing facility. For this, the recommended MVA regime included shallow groundwater monitoring wells near to where the injection wells were located, surface water sampling from lakes and rivers in the vicinity of the project, soil gas monitoring, and four deep monitoring wells. Mr. Sorensen stated that, in the end, CCS at Fort Nelson has been put on hold until a business case can be made, but the site has excellent potential for CO_2 storage. A key conclusion from the project was that an integrated approach to site characterization, modeling, and risk assessment can lead to an effective site-specific monitoring program, identify data gaps in site characterization, and increase the likelihood of project success by identifying and mitigating project risks. Mr. Sorensen closed his presentation by stating that both the Zama and the Fort Nelson Projects have been concluded.

19. Results from CSLF-recognized Project: Norcem Carbon Capture Project

Liv Bjerge representing project sponsor HeidelbergCement was not able to attend the meeting so Lars Ingolf Eide instead gave her presentation about the now-concluded Norcem Carbon Capture Project. 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. Project partners were Norcem, HeidelbergCement, and the European Cement Research Academy, and 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.

Ms. Bjerge’s presentation provided some results as well as lessons learned from the project. Testing the four technologies under real-world conditions, even at pilot scale, turned out to be extremely useful and overall, the project was deemed a success even though not all results were as expected. There were some difficulties in design for scaling up one of the processes from bench scale to pilot, and two of the technologies did not mature in terms of technology readiness level. The only technology supplier which managed to deliver a full-scale design including economic calculations was Aker Solutions, whose capture process was deemed to be the most mature of those tested. A project outcome was that the quality of results was highly dependent on the quality of the pilot facilities, with the conclusion that a commercial partner is of utmost importance for any technology that is being advanced toward commercialization. The most important and perhaps most obvious lesson learned is that conducting an aggressive pilot program of this nature almost always takes more time and resources than originally anticipated, so that should be factored into any test program. The Norcem Carbon Capture project has been of great importance for the proposed Norwegian full scale project, where CCS on a cement production facility is one of the three options.

20. Results from CSLF-recognized Project: CO_2 Capture Project Phase 4 (CCP4)

Mark Crombie, representing project sponsor BP, provided an overview of the CO_2 Capture Project, which has an overall goal of advancing CCS technology deployment and knowledge for the oil and gas industry. Phase 1 of the project, which ran from 2000 through 2004, concentrated on technology screenings through proof of concept. Phase 2, which ran from 2004 through 2009, featured intensive development of these technologies. Phase 3, which ran from 2009 through 2014, was the demonstration phase for these technologies. Phase 4, which began in 2014 and is scheduled to end in 2020, is focused on further advancement of these technologies.

Mr. Crombie described some of the results from CCP4. The purpose of Phase 4 is to increase the understanding of existing, emerging, and breakthrough CO_2 capture technologies and target a reduction in CO_2 capture cost by greater than 50%. To do this, CCP4 is supporting small- and pilot-scale techno-economic studies for four scenarios: refinery production, natural gas combined cycle, natural gas extraction, and heavy oil. In addition, specific studies are ongoing to assess two advanced solvent processes which are in different stages of development and to explore the techno-economic feasibility of CO_2 capture from small-scale natural gas-fueled engines. CCP4 also features a program component for ensuring safe and effective long-term CO_2 storage, with RD&D to address key CO_2 storage uncertainties and risks and a strategy which includes identifying key gaps in CO_2 storage assurance, developing projects with key third-party researchers to address these gaps, progressing these projects through technology readiness levels with an aim toward field testing of selected technologies, and rapid publication of results. Mr. Crombie closed his presentation with short descriptions of two other CCP4 components: including policy / incentives and communications. The former is intended to assist the development of legal and policy frameworks through project experiences in the regulatory process, while the latter assists the sharing of the CO_2 Capture Project's work and expertise.

21. Optimizing the Work of the Academic Task Force with the Technical Group

Sallie Greenberg gave a short presentation about the CSLF's Academic Council which was established by the CSLF Task Force following the 2015 CSLF Ministerial Meeting. The Academic Council comprises representatives from institutes and universities in CSLF member countries and serves in an advisory capacity to the Academic Task Force. The first meeting of the Academic Council was held in June 2016 as part of the CSLF Mid-Year Meeting in London. Dr. Greenberg stated that the Academic Council has three main focal areas: student training, practical learning and curriculum development; communication and outreach; and academic community and capacity building. The goals are to identify academic research linkages with CSLF Technical Group and Policy Group priorities; to determine where and how the CSLF can help leverage international collaborations, student exchanges, networks and funding opportunities to further CSLF goals; and to develop an overall plan of action. Dr. Greenberg reported that all of these focal areas have their own specific goals and objectives, and the Academic Council's activities in these areas have resulted in sets of recommendations.

Dr. Greenberg concluded her presentation by describing four recommendations for the Technical Group's consideration:

- Consider opportunities for research and capacity building through Technical Group member countries and organizations;
- Leverage existing synergies between the Academic Task Force, the CSLF Technical Group, Mission Innovation, and other organizations in order to advance the opportunities for CCUS deployment;

- Consider mechanisms to distill and disseminate technical research by the Technical Group member countries for high-level communication with the Policy Group, the Clean Energy Ministerial, and ministerial-level organizations; and
- Further engage and explore connections for the Academic Council to support Technical Group and Policy Group connections.

Ensuing discussion brought forth the idea that a survey could be sent to Academic Council members to see how much, if any, benefit the Technical Group's task force reports on various topics is to the general academic community in terms of informational value for both students and professors. There was consensus that this was a good idea, but further discussion was postponed until the agenda item on possible new Technical Group activities (see below).

22. Update from the Mission Innovation Carbon Capture Innovation Challenge (CCIC)

Tidjani Niass gave a short presentation about Mission Innovation and its CCIC. Mission Innovation is a Ministerial-level initiative that was launched in November 2015 at the Paris climate meeting and currently includes 22 countries plus the European Commission. Collectively, these countries represent 60% of the world's population, 70% of the global GDP, 80% of worldwide government investment in clean energy RD&D, and 67% of the total world greenhouse gas emissions. The overall goal of the Mission Innovation initiative is to accelerate 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.

Dr. Niass stated that the overall objective for the CCIC 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. A CCIC 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. Dr. Niass 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. Dr. Niass 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. Dr. Niass concluded his presentation by providing the next steps for the CCIC. These include delivering a report of CCIC activities at the upcoming 3rd Mission Innovation Ministerial (in May 2018), developing collaboration mechanisms, and fostering engagement with industry and other multilateral CCUS initiatives, including the CSLF.

23. Update from Working Group on Evaluating Existing and New Ideas for Possible Future Technical Group Actions

In follow-up to one of the outcomes from the December 2017 Technical Group meeting, Paul Ramsak gave a presentation about CO_2 capture and storage by mineralization, which had been one of the priority topics identified by a Technical Group working group which had been formed in 2017 to appraise all unaddressed items in the Technical Group's 2015 Action Plan, to propose new topics for appraisal, and to review past task force reports to see if any updates are warranted. Mr. Ramsak provided a short primer on the topic, stating that CO_2 capture and storage by mineralization is a niche opportunity for creating bulk construction and landscaping materials that could substitute for existing materials such as sand and gravel. In particular, accelerated binding processes use CO_2 to react with a range of minerals to form carbonates such as calcite and magnesite. In some cases, CO_2 becomes a new or substitute feedstock for concrete production, or sees use for curing or otherwise processing cement. Work on accelerated binding processes in the Netherlands, Germany, and the United Kingdom in recent years have resulted in its technology readiness level being improved. In particular, the United Kingdom's Carbon8 Project has three full-scale production facilities where CO_2 is being utilized to convert thermal wastes into building aggregates. In spite of these promising advances, Mr. Ramsak concluded his presentation by stating that it was nevertheless too early for the Technical Group to create a task force on CO_2 mineralization. Instead, it would be better to revisit and update the report from the Task Force on CO_2 Utilization, in particular the sections about non-EOR utilization options. This would result in a more useful input to the next iteration of the CSLF TRM. During brief ensuing discussion, there was consensus by the Technical Group to not form a new task force in this area.

Technical Group Chair Åse Slagtern then made a short presentation that summarized existing Technical Group activities and possible new ones. There are now only two active task forces besides the PIRT: Improved Pore Space Utilization (co-chaired by Australia and the United Kingdom) and CCS for Energy Intensive Industries (chaired by France). Ms. Slagtern stated that there are 24 potential new topics: eleven remaining from the original list of possible actions, eleven past task force topics which might merit update, and two new proposals. The members of the working group participated in a preference poll, which resulted in a shortlist of twelve topics and a "final four" of highest ranked topics:

1. Hydrogen as a Tool to Decarbonize Industries (which was the clear winner)
2. Reviewing Best Practices and Standards for Geologic Monitoring and Storage of CO_2
3. CO_2 Capture by Mineralization
4. Global Scaling of CCS

Of these, there had already been a consensus not to continue the Hydrogen Production and CCS as a task force and instead follow-up with a workshop. Also, there had been a consensus not to form a task force on CO_2 Capture by Mineralization. However, during ensuing discussion there was interest in following up on Mr. Ramsak's suggestion to revisit the topic of non-EOR CO_2 utilization, with the caveat that it should not be duplicative of similar studies done by other organizations. The Technical Group's Task Force on Utilization Options for CO_2 had been active between 2011 and 2013 and had produced two reports (which are archived at the CSLF website). There was consensus to re-form that task force to examine non-enhanced hydrocarbon recovery CO_2 utilization options, with the United States as Chair and participation from Australia, Canada, France (pending endorsement by its Club CO_2), the Netherlands, and Saudi Arabia. The Task Force was requested to develop a plan and timeline to be presented at the next Technical Group meeting.

Discussion then resumed from the previous day's PIRT meeting on how to measure progress on recommendations from the TRM. The PIRT had reached consensus that the details for moving forward in this area were not solvable at the current meeting but that the Secretariat would moderate an offline discussion for any delegates who wanted to have a role. However, there was consensus that this should instead be a full Technical Group activity, as there was interest in also evaluating the present form of Technical Group task forces as well as alignment with the CSLF Academic Task Force and Communications Task Force. Sallie Greenberg volunteered to take the lead in organizing an informal group to determine what can be done in this area and how to do it. This could include a survey of some kind and also participation from outside organizations such as Mission Innovation and other CCUS organizations. Progress, including a proposed way forward, will be reported at the next Technical Group meeting.

24. Update on Future CSLF Meetings

Richard Lynch stated that there was nothing yet to report about the 2019 CSLF meetings and that expressions of interest in hosting a meeting would be welcome. Max Watson reported that the 2018 Annual Meeting would be held in Melbourne, Australia on 16-18 October, which is the week prior to the IEAGHG's GHGT conference. The PIRT meeting would be on Tuesday, October 16th, the Technical Group meeting on Wednesday, October 17th, and the Policy Group meeting on Thursday, October 18th. Additional details would also be forthcoming soon.

25. Open Discussion and New Business

Three of the four CSLF regional stakeholder engagement leads were in attendance and presented brief reports. Pieter Smeets, representing the Middle East / Africa region, stated that holding a stakeholder workshop was beneficial and that the next workshop for that region would not occur until the roll-up period for the next CSLF Ministerial meeting. Jiro Tanaka, representing the Asia / Pacific region, stated that a stakeholder survey was done prior to the 2017 CSLF Ministerial and that results were summarized into a report. To maximize regional stakeholder participation, this approach will be continued for the roll-up to the next Ministerial. Ton Wildenborg, representing the Europe region, stated that an active group of European stakeholders is being assembled to send clear messages about CCS and its technologies to decision makers in the European Commission, and that a regional stakeholder meeting will be held about every two years.

David Savary reported that a symposium titled "International Overview of CO_2 Utilisation" is being hosted by France's Club CO_2 on July 2nd in Paris. The Symposium is being organized with two themes: "International Status of Carbon Capture and Utilization (CCU)" which will have a wide overview of global developments about CO_2 utilization, and "Which tools to enhance CCU?" whose focus will be on exchange among participants on standardization and life cycle assessment as levers for deployment of CCU.

Paolo Deiana mentioned that the Sixth Annual Sulcis CCS Summer School will be held on June 18-22 at the Sotacarbo Research Centre on Italy's Sardinia Island. Lectures during the five days of the event will cover the range of technologies developed for capture, utilization, and geologic storage of CO_2, for which the Sulcis basin is an ideal laboratory for experiments. The summer school is intended for PhD and Postdoctoral students in engineering curricula and social aspects relevant to CCS.

Brian Allison stated that the United Kingdom CCS Research Centre's Pilot-Scale Advanced CO_2 Capture Technology (PACT) facility is now the lead for the International Test Center Network (ITCN). There was consensus that a presentation about the ITCN be included in the next Technical Group meeting.

26. Closing Remarks / Adjourn

Technical Group Chair Åse Slagtern thanked the delegation from Italy for hosting the meeting, the CO_2GeoNet Association for its help in arranging the meeting's venue and logistics, the Secretariat for its pre- and post-meeting support, and the delegates for their active participation. She then adjourned the meeting.

Summary of Meeting Outcomes

- The ENOS project is recommended by the Technical Group to the Policy Group for CSLF recognition.
- The Task Force on Hydrogen with CCS will not continue beyond its now-completed "Phase 0" activities. Instead, a workshop on Hydrogen with CCS will be organized for a future CSLF meeting. A report on the task force's "Phase 0" findings will be published at the CSLF website.
- 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 BECCS Task Force has submitted its final report and has disbanded.
- The Technical Group will not form a new task force on CO_2 Capture and Storage by Mineralization, as it was deemed premature to do so.
- The Technical Group has formed a task force to examine non-EOR CO_2 utilization options, which will develop a plan and timeline to be presented at the next Technical Group meeting. Task force members are the United States (Chair), Australia, Canada, France, the Netherlands, and Saudi Arabia.
- Follow-up on recommendations from the 2017 TRM is now a full Technical Group activity instead of being assigned to the PIRT. This activity will also include measuring the use of Technical Group task forces as well as alignment with the CSLF Academic Task Force and Communications Task Force. United States delegate Sallie Greenberg will organize an informal group to determine what can be done. Progress, including a proposed way forward, will be reported at the next Technical Group meeting.
- A presentation about the ITCN will be included in the next Technical Group meeting.

Carbon Sequestration Leadership Forum
www.cslforum.org

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.

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CSLF Technical Group Action Plan Status

(as of August 2018)

Current Actions

- Improved Pore Space Utilisation (*Task Force co-chairs: Australia and United Kingdom*)
- CCS for Industries *(Task Force chair: France)*
- Non-EOR CO_2 Utilization Options (*Task Force chair: United States*)
- Ad Hoc Committee for Task Force Maximization and Knowledge Sharing Assessment (*Committee chair: United States*)

Potential Actions

- Geo-steering and Pressure Management Techniques and Applications [*Note: Geo-Steering has been incorporated into Improved Pore Space Utilisation action.*]
- 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 *
- Global Scaling of CCS *

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

Completed Actions (*previous five years*)

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

Draft Minutes of the CSLF Policy Group Meeting

Tuesday, 5 December 2017

Rosewood Abu Dhabi

Abu Dhabi, United Arab Emirates

List of Attendees

Policy Group Delegates

Australia:	Josh Cosgrave, Tim Sill
Brazil:	Paulo Pires
Canada:	Claude Gauvin
China:	Jinfeng Ma
European Commission:	Jeroen Schuppers
France:	Didier Bonijoly, Dominique Copin
Germany:	Almut Fischer
Italy:	Sergio Persoglia
Japan:	Ryozo Tanaka, Jiro Tanaka
Korea:	Chong Kul Ryu, Mi Hwa Kim
Mexico:	Leonardo Beltrán, Jazmín Mota
Netherlands:	Laurens Baas, Harry Schreurs
Norway:	Stig Svenningsen
Romania:	Constantin Stefan Sava, Anghel Sorin
Saudi Arabia:	Khalid Abuleif (Vice Chair), Hamoud AlOtaibi, Abdullah Alsarhan
South Africa:	Landi Themba, Noel Kamrajh
United Arab Emirates:	Fatima Al Shamsi, Arafat Al Yafei
United Kingdom:	Brian Allison (Vice Chair)
United States:	Steve Winberg (Chair), Jarad Daniels, Mark Ackiewicz

Organization Representatives

Global CCS Institute:	Jeff Erikson
IEA:	Tristan Stanley
IEAGHG:	Tim Dixon

CSLF Secretariat

Richard Lynch, Adam Wong

Invited Speakers

Australia:	Andrew Barrett, Geoscience Australia (PIRT Chair)*
Norway:	Åse Slagtern, Research Council of Norway (Technical Group Chair)*
	Lars Ingolf Eide, Research Council of Norway*
Saudi Arabia:	Tidjani Niass, Saudi Aramco
United Arab Emirates:	Matar Al Neyadi, Ministry of Energy
United States:	Sallie Greenberg, University of Illinois
	Barry Worthington, United States Energy Association
World Bank (Consultant):	Brendan Beck

Observers

Australia:	Max Watson*
Korea:	Chang-Keun Yi*, Kwon Yi Kyun
Japan:	Leandro Figueiredo
Netherlands:	Angus Gillespie
Norway:	Arne Graue
Saudi Arabia:	Wolfgang Heidug, Pieter Smeets
United Arab Emirates:	Mohammad Abu Zahra
United Kingdom:	Gardiner Hill, Tom Howard-Vyse, Ceri Vincent

United States: Damian Beauchamp, Bill Brown, Frank Morton, Chris Romans, Ed Steadman

*CSLF Technical Group Delegate

1. **Welcome and Opening Statement**
   Steven Winberg, Policy Group Chair, United States, called the meeting to order and thanked the United Arab Emirates (UAE) and the Ministry of Energy for hosting.

2. **Introduction of Delegates**
   Delegates around the table introduced themselves. Nineteen of the twenty-six CSLF members were present, including representatives from Australia, Brazil, Canada, China, European Commission, France, Germany, Italy, Japan, Korea, Mexico, Netherlands, Norway, Romania, Saudi Arabia, South Africa, United Arab Emirates, United Kingdom, and United States.

3. **Host Country Welcome**
   H.E. Dr. Matar Al Neyadi, Undersecretary of the Ministry of Energy, UAE, welcomed attendees to the UAE. H.E. Al Neyadi stated that carbon capture, utilization, and storage (CCUS) is rapidly evolving from joint oil and gas producers to address sustainability and climate change. He commended the CSLF for working towards the future of CCUS.

4. **Adoption of Agenda**
   The agenda was adopted with three changes:
   1) "Report from the CSLF Academic Council" from Sallie Greenberg, Academic Council Co-Chair, United States, was moved to the afternoon, between "Mission Innovation: Capture Challenge Update" from Tidjani Niass, Saudi Arabia and "Clean Energy Ministerial Update" from Jarad Daniels, United States.
   2) "Report from the Financing for CCS Projects Task Force" was presented by Didier Bonijoly, Acting Task Force Chair, France in place of Bernard Frois, Task Force Chair, France.
   3) "Financing CCS" was presented by Brendan Beck, Energy Consultant to the World Bank, in place of Nataliya Kulichenko, World Bank.

5. **Review and Approval of Minutes from May 2017 Policy Group Meeting in Abu Dhabi**
   The Minutes from the CSLF Policy Group Meeting on May 4, 2017, in Abu Dhabi, UAE were approved without any changes.

6. **Report from CSLF Secretariat**
   Adam Wong, CSLF Secretariat, provided a brief summary of the action items from the CSLF Policy Group Meeting on May 4, 2017, in Abu Dhabi, UAE. All action items have been completed or are currently in progress.

7. **Report from CSLF Stakeholders**
   Barry Worthington, United States Energy Association gave an update from the CSLF Stakeholders. Recent Stakeholder regional meetings were held in the Americas, Europe, Middle East/Africa, and Asia/Pacific. As a result, each Regional Champion implemented stakeholder input processes as appropriate for their region. Stakeholder messages to the Ministers include a need to identify commonality among regions due to the different messages among regions, improve overall communication, and increase communication to political leaders, policy makers, and regulators. Moving forward, the Stakeholders will endorse the regional approach and hold annual or bi-annual stakeholder meetings, access mechanisms for improvement, and compile a comprehensive report to the Policy Group.

8. **International Energy Agency CCS Activities Update**
   Tristan Stanley, International Energy Agency (IEA) provided an update from the IEA, which is focusing on the role of carbon capture and storage (CCS) in climate scenarios and securing investment. In order to meet various global CO_2 reduction scenarios, CCS will need to be a key solution. While there have been some investments in CCS, more is needed. The IEA hosted a

CCUS Summit, held ahead of the IEA's 2017 Ministerial Meeting and co-chaired by U.S. Secretary of Energy Rick Perry and IEA Executive Director Dr. Fatih Birol. Participants included ministers and top government officials from Australia, Canada, Japan, Mexico, Norway, Poland, the Netherlands, the United Kingdom, and European Commission. Industry representatives included CEOs and senior executives from ExxonMobil, Royal Dutch Shell, BP, Statoil, Chevron, Total Glencore, Suncor Energy, GE Power, Dow Chemical, Mitsubishi Heavy Industries, and Port of Rotterdam. At the CCUS Summit, the IEA also released a report on "The "Five Keys" to unlock CCS investment," with the five keys being:

1. Harvest low-hanging fruit to build CCS deployment and experience from the ground up.
2. Tailor policies to shepherd CCS through the early deployment phase and to address unique integration challenges for these facilities.
3. Target multiple pathways to reduce costs from technology innovation to progressive financial mechanisms.
4. Build CO_2 networks to better support transport and storage options.
5. Strengthen partnerships and cooperation between industry and government.

9. Global CCS Institute Update

Jeff Erikson, Global CCS Institute (GCCSI) updated the Policy Group on GCCSI activities. Recently, the GCCSI participated in the United Nations Framework Convention on Climate Change (UNFCCC) in Bonn, Germany from November 6-17. The GCCSI has also done global analysis on country-specific national CCS policy, showing how country legal and regulatory policy support can lead to large-scale CCS facilities.

10. Report from CSLF Technical Group

On behalf of the Technical Group, Åse Slagtern, Technical Group Chair, Norway, reported out on recent Technical Group activities. Overall, the Technical Group is making progress toward key CSLF goals by developing a forward-looking vision utilizing how to get there (CSLF Technology Roadmap), facilitating knowledge sharing among CCUS technology developers and users (Project Engagement Strategy), encouraging collaborative activities among CSLF members (CSLF-recognized Projects), and developing messages and recommendations in specific CCUS technology areas (Task Forces). Chaired by Australia, the 2017 CSLF Technology Roadmap was completed on schedule and on time for the 2017 CSLF Ministerial Meeting.

Ms. Slagtern summarized highlights and outcomes from the previous day's Technical Group Meeting, which included updates from four Technical Group Task Forces: Off-Shore CO_2-EOR Bioenergy with CCS (Bio-CCS and BECCS), Improved Pore Space, Utilisation, and Industrial CCS. The Technical Group recommended that the Policy Group provide CSLF recognition to the CO2CRC Otway Project Stage 3. Located in Australia, this project builds on Otway project Stages 1 &2 (both CSLF recognized projects), with the goal to validate cost and operationally effective subsurface monitoring technologies that will accelerate implementation of commercial CCS projects. The Policy Group approved the CO2CRC Otway Project Stage 3 project for CSLF recognition.

The Technical Group also recommended that the Policy Group approve some recommended changes to the CSLF Terms of Reference (ToR). These recommended changes included updating project recognition procedures, ensuring consistency with CSLF Charter, and other miscellaneous corrections and updates. The Policy Group approved these recommended changes.

11. Report on CSLF Technology Roadmap (TRM)

Andrew Barrett, TRM Working Group Chair, Australia, and Lars Ingolf Eide, TRM Editor, Norway, presented an overview of the 2017 CSLF Technology Roadmap. There were numerous changes since the last TRM in 2013, including the focus moving away from R&D to implementation and learning from experience (CCS works), and more emphasis on development of clusters and hubs, and on industrial and biomass CCS. A key priority recommendation is that 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.

12. Report from Regulatory Task Force
Ryozo Tanaka, Task Force Chair, Japan, gave a report from the Regulatory Task Force, which was originally proposed by Japan at the CSLF Annual Meeting in Tokyo in October 2016. The Task Force objective is to explore practical regulations and permitting process for geological CO_2 storage. For the 2017 CSLF Ministerial Meeting, the Task Force has prepared a report of findings and recommendations from case studies of project experiences with the regulatory process for CO_2 storage. These findings are complementary to work done by the IEA and GCCSI. A total of 15 findings are included in the report, with the key conclusion being that In the future, experiences for the next generation of CCS projects should be examined to look into how the issues identified in the findings have been resolved in various jurisdictions. Many of the issues, including operator's finance responsibilities, may be specific to a first wave of CCS projects that have no or limited precedent experiences in permitting for geological CO_2 storage.

13. Report from the Communications Task Force
Hamoud AlOtaibi, Task Force Chair, Saudi Arabia spoke on recent activities of the CSLF Communications Task Force. The Task Force's strategy has included efforts to expand strategic engagement, simplify CSLF messaging, expand message delivery mechanisms, and a refresh of the CSLF's digital profile. Ongoing activities include website development, CSLF Ministerial and stakeholder liaison, and maintaining and developing core materials. Activities proposed for 2018 are to promote the 2017 CSLF Communique, promote Technology Roadmap with all stakeholders, review name / brand of CSLF, host Ministerial side event at COP24, develop a powerpoint template for members, support the proposed CCUS initiative under CEM9, deepen political engagement to 2019, explore strategic AR6 communications opportunities (Working Group III), and explore opportunities with media for CSLF-approved CCS projects.

14. Report from the Capacity Building Governing Council
Stig Svenningsen, Governing Council Chair, Norway, provided an update from the Capacity Building Governing Council (Council). To date, the Council has approved 19 capacity building projects in 6 countries, with 13 projects completed and 6 projects in progress. Funds currently available, after approved projects, are AUS $930,078. Since the CSLF Policy Group Meeting on May 4, 2017, in Abu Dhabi, UAE, the Council has approved one project and made changes to the Council's Terms of Reference.

15. Report from the Financing for CCS Projects Task Force
Didier Bonijoly, Acting Task Force Chair, France, provided a report from the Financing for CCS Projects Task Force, in place of Bernard Frois, Task Force Chair, France, who sent his regrets. Climate change, and with it CCS, now has a driver outside of regulation. This can be a more stable driver for CCS than policy, which has gone through wild swings in various democracies (U.S., UK, Australia). There was also great interest for a CCS side-event at COP23, as everyone agreed that there are no technical showstoppers when it comes to realizing CCS. He provided updates on CCS perspectives in countries including, Norway, UK, and the U.S., with the conclusion that CCS needs to be associated with clean energy, while also being provided with a suite of incentives and regulations.

16. Financing CCS in Developing Countries
Brendan Beck, Energy Consultant to the World Bank, on behalf of Nataliya Kulichenko, World Bank, updated the Policy Group on the World Bank financing CCS in developing countries. The World Bank CCS Trust Fund (CCS TF) was established in December 2009, with the main objectives to support strengthening capacity and knowledge building, to create opportunities for developing countries to explore CCS potential, and to facilitate inclusion of CCS options into developing country low-carbon growth strategies and policies. Contributions to the CCS TF to date total US $70 million from the UK, Norway, and the Global CCS Institute. Phase 1 of the CCS TF was completed in 2015, and included US $8 million allocated to desk-top CCUS studies in nine countries. Phase 2 of the CCS TF commenced in 2014, and has allocated US $49 million to four CCUS pilot projects in Mexico and South Africa.

In order to finance CCUS in developing countries, the World Bank focuses on early-opportunity projects that have host government support, high-concentration CO_2 sources, industrial CO_2 uses, and EOR opportunities. These factors are gauged in combination with support opportunities from climate finance, concessional finance, payment guarantees, and private sector participation

17. Mission Innovation: Carbon Capture Innovation Challenge Update

Tidjani Niass, Saudi Arabia, presented an update from the Mission Innovation: Carbon Capture Innovation Challenge (CCIC). Co-led by Saudi Arabia and the U.S., the CCIC has 20 of the 23 Mission Innovation country members with the objective to enable near-zero CO_2 emissions from power plants and carbon intensive industries. CCIC held a CCUS Experts' Workshop in Houston, Texas, U.S., from September 25-29 with 257 participants from academy and industry from 22 countries for 13 parallel panel discussions. Next steps include the publication of a workshop report in early 2018, the development of collaboration mechanisms, further fostering engagement with industry, and preparations for the 3rd Mission Innovation Ministerial Meeting (MI-3) in May 2018.

18. Report from the CSLF Academic Council

Sallie Greenberg, Academic Council Co-Chair, United States, updated the Policy Group on the recent activities from the CSLF Academic Council, an advisory group comprised of representatives from institutes and universities, and established by the CSLF Academic Task Force following the 2015 Ministerial Meeting. The Academic Council has three areas of focus: 1. Student training, practical learning, and curriculum development; 2. Communications and outreach; and 3. Academic community and capacity building. Through efforts in these three areas of focus, the Academic Council provided five recommendations to the Policy Group: 1. Engage and explore connections for Academic Council to support Policy Group; 2. Design and conduct consultation process to generate CSLF-supported guidelines for Stakeholder Engagement; 3. Consider potential through CEM/CSLF connections; 4. Evaluate and refine messaging from CSLF; and 5. Leverage existing synergies.

19. Clean Energy Ministerial Update

Jarad Daniels, United States, provided an update on a proposed CCUS Initiative under the Clean Energy Ministerial (CEM). At the 8th Clean Energy Ministerial (CEM8) in Beijing in June, U.S. Secretary of Energy Rick Perry noted that the U.S. feels strongly that CCUS and nuclear should be included within the suite of clean energy technologies under consideration by CEM. Currently, the U.S., along with Canada, Japan, Mexico, Norway, Saudi Arabia, the UAE, and United Kingdom, are jointly proposing a new CCUS initiative which will strengthen the framework for public-private collaboration on CCUS, while complementing the efforts and adding coordinated value beyond the activities of existing organizations and initiatives. Integrating conversations around CCUS in the CEM allows the technology to be considered outside the silo of CCUS proponent governments to date, and potentially widens the range of support. The conversation continued last month when Secretary Perry and IEA Executive Director Birol co-chaired the CCUS Summit on the margins of the IEA Ministerial.

Delegates then discussed what CCUS in CEM would mean for the CSLF. It was agreed that while there are already multiple CCUS initiatives in place, the CSLF also campaigns to get CCUS into other clean energy conversations, including other ministerial meetings. Therefore, the CSLF should also work to get CCUS into the CEM. It was agreed that the United States would take the lead to draft a proposal to stand up a CCUS Initiative under CEM, and interested CEM members should contact the United States.

20. 2017 CSLF Ministerial Meeting

Jarad Daniels, United States, reviewed the agenda for the following day's CSLF Ministerial Meeting. The morning will feature scene-setting presentations and key CSLF perspectives from the Stakeholders, Technical Group, and Policy Group. The day will feature three panel discussions, the first on national and international policies to build business cases for CCUS, the second a CCUS project showcase with regional highlights, and the third panel on CCUS infrastructure development. The late afternoon will feature both an open and then a closed session for the Ministers, concluding with a press conference.

21. Review of CSLF Policy Group Messages to Ministers

Jarad Daniels, United States, reviewed the CSLF Policy Group Messages to the Ministers, which included updates and accomplishments from each of the Policy Group Task Forces. Delegates suggested additional items to include. These items were included in the final presentation to the CSLF Ministers.

22. Future CSLF Meetings

Australia stated that it will host the 2018 CSLF Annual Meeting on the margins of the IEA Greenhouse Gas R&D Programme (IEAGHG) 14th Greenhouse Gas Control Technologies (GHGT) Conference from October 21-26 in Melbourne, Australia. The CSLF is looking for a country to host a potential 2018 CSLF Mid-Year Meeting.

23. Review of Draft 2017 CSLF Ministerial Communiqué

Jarad Daniels, United States, led the discussion regarding the draft 2017 CSLF Ministerial Communiqué. Delegates provided numerous suggested changes and edits, which were incorporated into the updated draft. A final draft 2017 CSLF Ministerial Communiqué was approved by the Policy Group, and circulated via email by the CSLF Secretariat for approval by the CSLF Ministers.

24. Open Discussion and New Business

No new business was raised.

25. Action Items and Next Steps

Jarad Daniels, United States, provided a summary of the day's Policy Group Meeting, and noted the significant agreements and action items. The Policy Group reached a consensus on the following items:

- Approved the CO2CRC Otway Project Stage 3 project for CSLF recognition
- Approved revisions to the CSLF Terms of Reference

Action items from the meeting are as follows:

Item	Lead	Action
1	All delegates	Send updated country CCUS developments, including any CCUS-related quotes from country Ministers, to the CSLF Secretariat for the CSLF website country pages
2	Communications Task Force	Prepare generic CSLF presentation for use by CSLF members and look into potential key engagement opportunities to utilize the presentation, including the 2018 United Nations Climate Change Conference (COP24) and Clean Energy Ministerial (CEM)
3	Communications Task Force	Distribute CSLF documents, including both the 2017 CSLF Ministerial Communiqué and the 2017 CSLF Technology Roadmap
4	Capacity Building Governing Council	Solicit additional CSLF Capacity Building project proposals
5	United States	Take the lead to draft a proposal to stand up a CCUS Initiative under the Clean Energy Ministerial
6	United States	Update the Policy Group Message to Ministers with new input from delegates
7	Delegates and CSLF Secretariat	Find a country to host a potential 2018 CSLF Mid-Year Meeting

26. Closing Remarks / Adjourn

Jarad Daniels, United States, closed the meeting. He also highlighted the approval of the CO2CRC Otway Project Stage 3 project for CSLF recognition. He thanked all of the participants and the government of the UAE for hosting the event, and looked forward to the following day's CSLF Ministerial Meeting.

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.

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

Active and Completed CSLF Recognized Projects

(as of May 2018)

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. 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

28. 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

29. 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

30. 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

31. 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

32. 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

33. 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

34. 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

35. 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

36. 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

37. 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

38. 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

39. 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

40. 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

41. 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

42. 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

43. 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

44. 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

45. 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

46. 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

47. 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

48. 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

49. 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

50. SECARB Early Test at Cranfield Project

Nominators: United States (lead) and Canada

This is a large-scale project, located in southwestern Mississippi in the United States, which involves transport, injection, and monitoring of approximately one million tonnes of CO_2 per year into a deep saline reservoir associated with a commercial enhanced oil recovery operation, but the focus of this project will be on the CO_2 storage and monitoring aspects. The project will promote the building of experience necessary for the validation and deployment of carbon sequestration technologies in the United States, and will increase technical competence and public confidence that large volumes of CO_2 can be safely injected and stored. Components of the project also include public outreach and education, site permitting, and implementation of an extensive data collection, modeling, and monitoring plan. This "early" test will set the stage for a subsequent large-scale integrated project that will involve post-combustion CO_2 capture, transportation via pipeline, and injection into a deep saline formation.

Recognized by the CSLF at its Warsaw meeting, October 2010

51. 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

52. 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

53. 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

54. 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

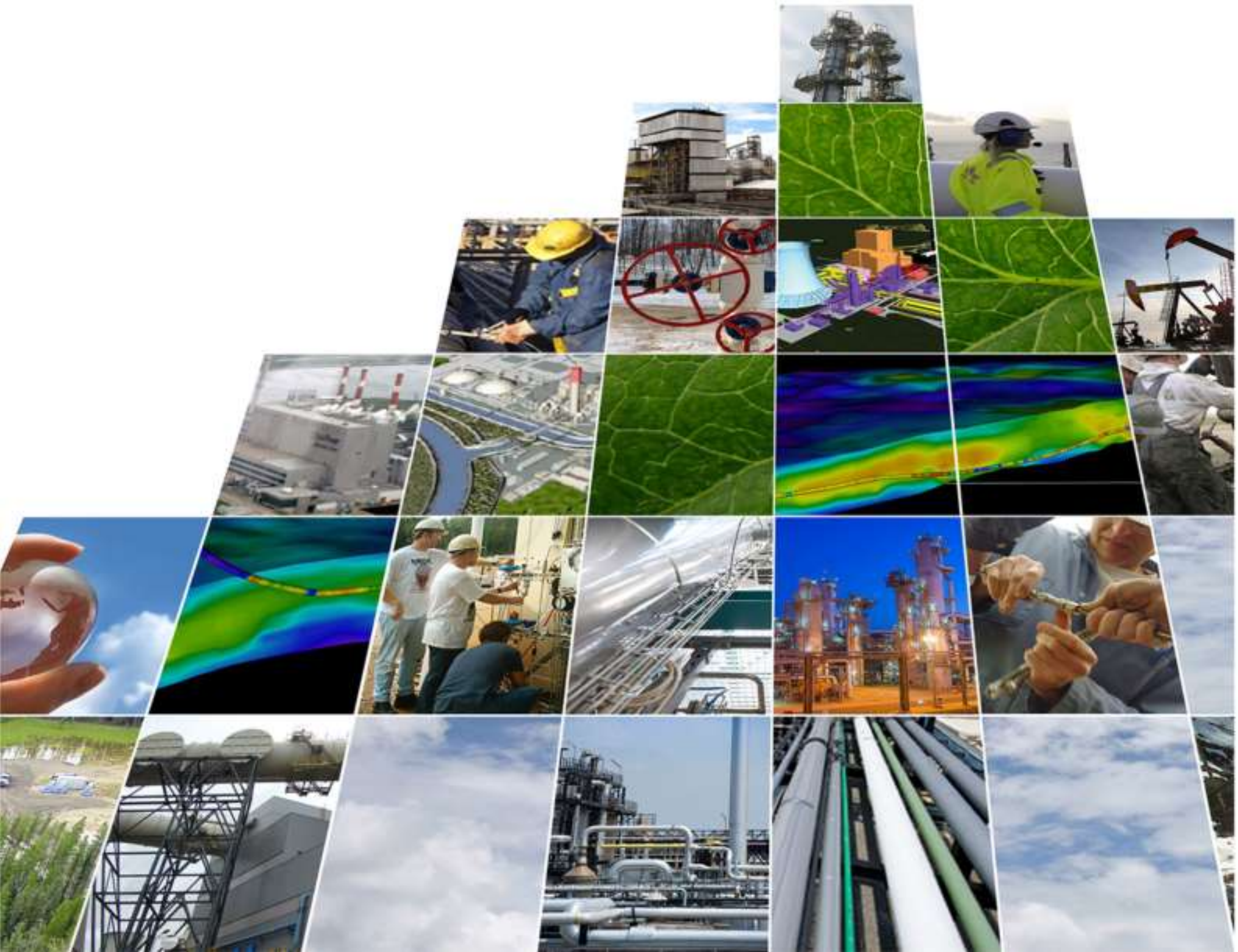
Note: "Lead Nominator" in this usage indicates the CSLF Member which proposed the project.

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

> ***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.

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.

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,

[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

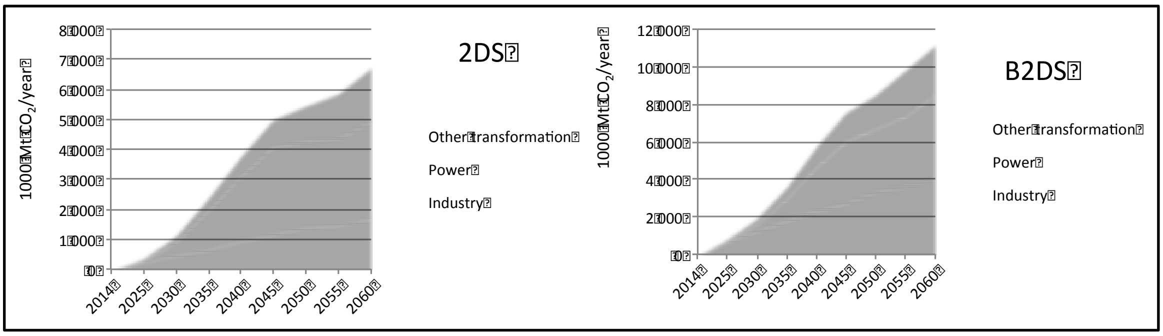

Figure 2.1. *CO_2 captured and stored per year to achieve the 2°C Scenario (left panel) and Beyond 2°C Scenario (right panel), in 1,000 Mt CO_2/year (after IEA 2017a).*

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).

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.

> 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).

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

[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.

[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

United States: John Thompson

United Kingdom: Sarah Tennison and Jon Gibbins

South Africa: Sibbele Heikamp

Australia: Paul Feron

Japan: Takayuki Higahsii

Global Carbon Capture and Storage Institute

Valuable input on the Executive Summary was received from Sallie Greenberg, University of Illinois, and Communications Task Force members Jeff Erikson, Tom Howard-Vyse, Ron Munson and Hamoud Otaibi.

Amy Cutter, BEIS, UK, and Valerie Riedel, Energetics, suggested valuable improvements to language.

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 $/t$CO_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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