carbon sequestration leadership forum

CSLF

Technical Group Meeting
Venice, Italy

Meeting Documents Book

April 22–23, 2018

Carbon Sequestration Leadership Forum

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2018 CSLF TECHNICAL GROUP MEETING DOCUMENTS BOOK

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Carbon Sequestration Leadership Forum

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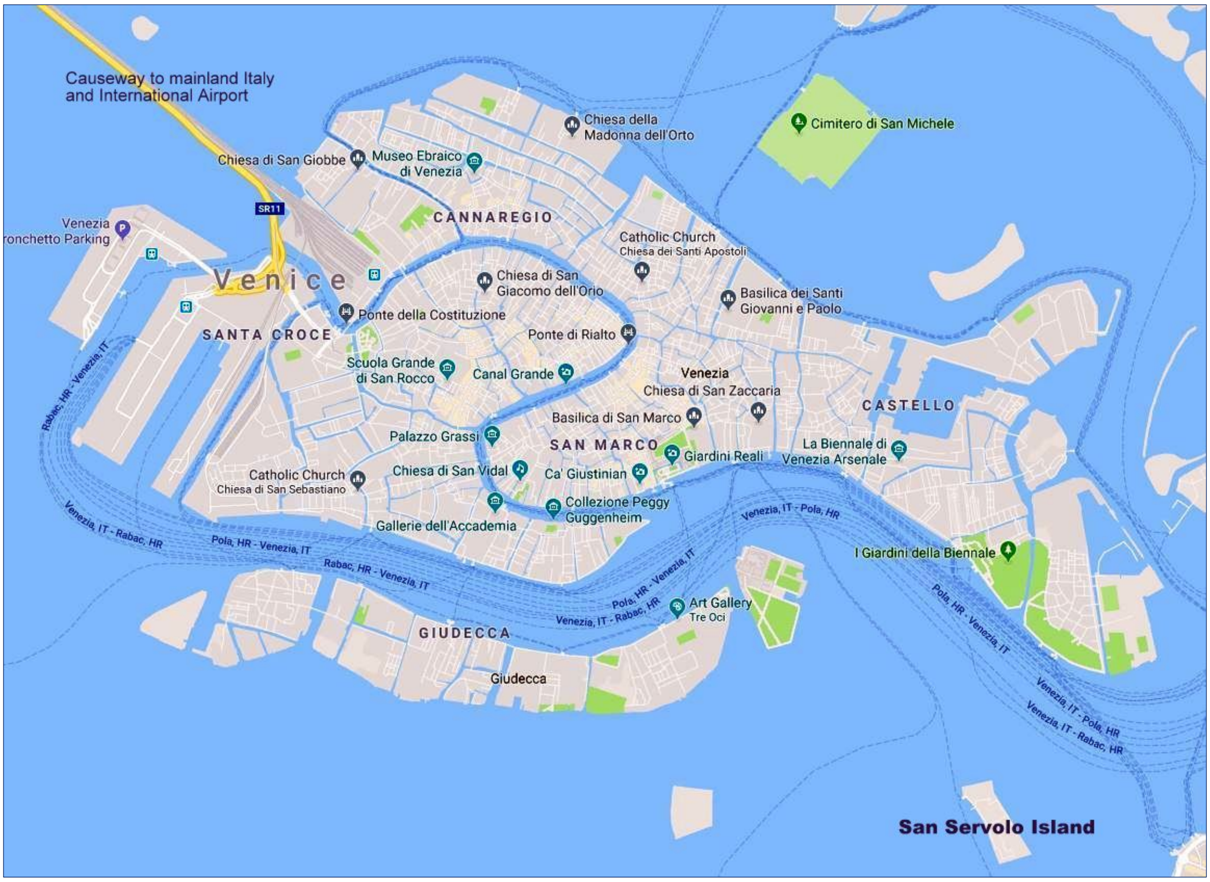
OVERALL SCHEDULE

2018 CSLF Technical Group Meeting
San Servolo Island, Venice, Italy

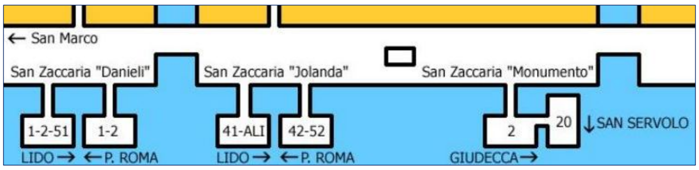
	Sunday April 22	Monday April 23	Tuesday April 24	Wednesday April 25	Thursday April 26
Morning		**Meeting of CSLF Technical Group** *Room 1E* *(meeting starts at 9:00am)*	CO_2 GeoNet Open Forum (not part of CSLF meeting)	CO_2 GeoNet Open Forum (not part of CSLF meeting)	CO_2 GeoNet Open Forum (not part of CSLF meeting)
Afternoon	**Meeting of CSLF Projects Interaction and Review Team (PIRT)** *Room 6* *(meeting starts at 2:00pm)*	**Meeting of CSLF Technical Group** (continues)	CO_2 GeoNet Open Forum (not part of CSLF meeting)	CO_2 GeoNet Open Forum (not part of CSLF meeting)	CO_2 GeoNet Open Forum (not part of CSLF meeting)

Meeting Venue Information



The 2018 CSLF Technical Group Meeting will take place on **San Servolo Island**, located in the Venetian Lagoon southeast of the city center. The Marco Polo International Airport is located on the Italian mainland and it is possible to travel to Venice from the airport by both ground transport and water buses.

To get from Venice to San Servolo Island, take the no. 20 "Vaporetto" water bus which departs from San Zaccaria "Monumento" in front of the Londra Palace Hotel. There is frequent service throughout the day, and the transit time is about 10 minutes.



The water bus pier at San Servolo Island is adjacent to the Hotel Centro Soggiorno, and the CSLF meeting will be held in Room 1E of the hotel.

San Servolo Island is the location of Venice International University, and the island is the University's campus. In that regard, rooms at the Hotel Centro Soggiorno are in college-style residential halls that are satellite buildings to the main building (where Room 1E is located). A small room block has been arranged at the Hotel Centro Soggiorno for those who would like to stay very close to the meeting venue. Rates are €80 for single room and €110 for twin room, using the same hotel accommodation form as for the CO_2 GeoNet Open Forum Meeting (which will also take place on San Servolo Island, starting on April 24).

For those wanting to stay in Venice instead of on San Servolo Island, there are many other good hotel options, including the following:

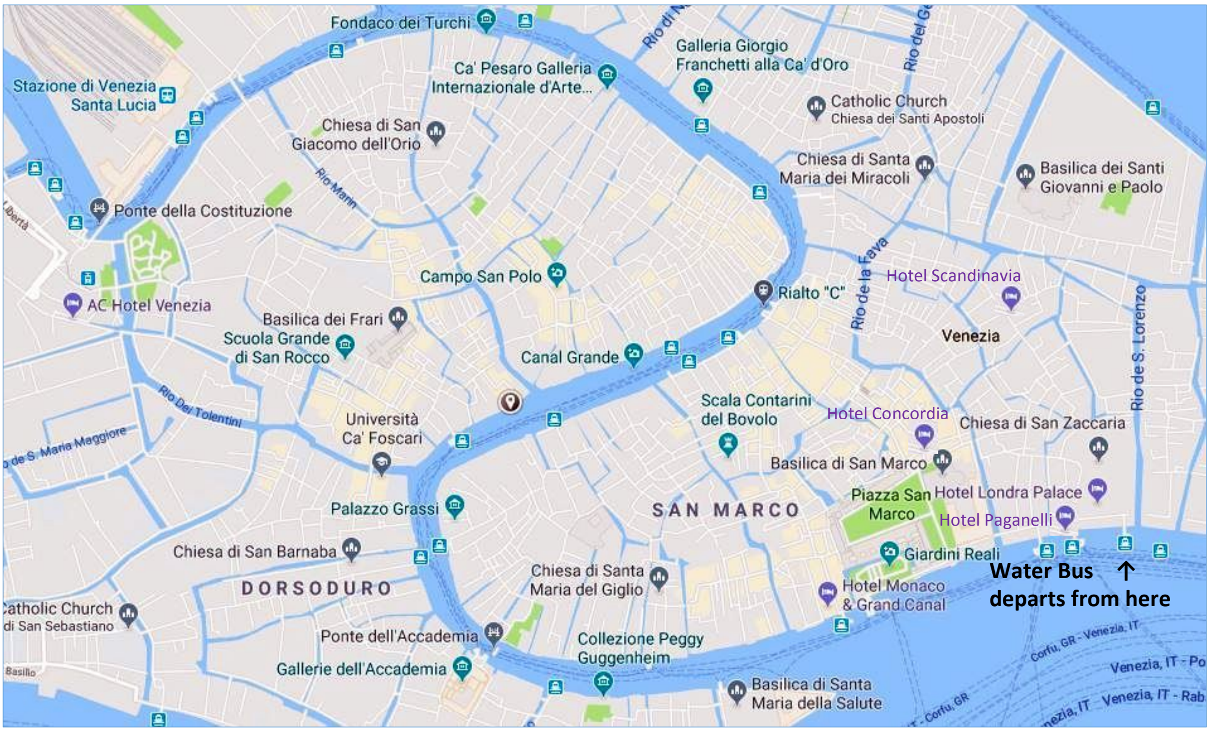
Hotel Concordia (Calle Larga San Marco 367; tel: +39 041 520 6866). Use the code OGSVENICE to obtain 15% discount on room rate.

Hotel Monaco & Grand Canal (Piazza San Marco 1332; tel: +39 041 520 0211).

Hotel Paganelli (Riva degli Schiavoni 4182; tel. +39 041 522 4324).

Hotel Scandinavia (Campo S. Maria Formosa, 5240, 30122 Castello; tel. +39 041 522 3507).

AC Hotel Venezia (Rio Tera Sant'Andrea 466; tel: +39 041 852 0321).



Carbon Sequestration Leadership Forum

Prepared by CSLF Secretariat

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Draft Agenda

CSLF PROJECTS INTERACTION AND REVIEW TEAM (PIRT)

Room 6, Hotel Centro Soggiorno, San Servolo Island
Venice, Italy

22 April 2018

14:00-16:30

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 December 2017** *(3 minutes)*
   Andrew Barrett, PIRT Chair, Australia

5. **Report from Secretariat** *(10 minutes)*
   - Review of Previous PIRT Meeting (Abu Dhabi, December 2017)
   - Summary of CSLF Recognized Projects

   Richard Lynch, CSLF Secretariat

6. **Review of Project Proposed for CSLF Recognition:**
   Enabling Onshore CO_2 Storage in Europe (ENOS) *(30 minutes)*
   Marie Gastine, ENOS Coordinator, BRGM, France

7. **Update from PIRT Working Group to Explore Feasibility for Measuring Progress on Recommendations from 2017 CSLF Technology Roadmap** *(30 minutes)*
   Lars Ingolf Eide, Norway

8. **Update from Working Group on Evaluating Existing and New Ideas for Possible Future Technical Group Actions** *(30 minutes)*
   Åse Slagtern, Technical Group Chair, Norway
   PIRT Delegates and Meeting Attendees

9. **General Discussion and New Business** *(10 minutes)*
   PIRT Delegates and Meeting Attendees

10. **Action Items and Next Steps** *(5 minutes)*
    Richard Lynch, CSLF Secretariat

11. **Closing Comments / Adjourn** *(5 minutes)*
    Andrew Barrett, PIRT Chair, Australia

Draft: 12 April 2018
Prepared by CSLF Secretariat

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CSLF Technical Group Meeting

Room 1E, Hotel Centro Soggiorno, San Servolo Island
Venice, Italy
23 April 2018

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

09:00-10:30 **Technical Group Meeting**

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

2. **Host Country Welcome** *(7 minutes)*
   Marcello Capra, Senior Expert, Ministry of Economic Development, Italy

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

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

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

6. **Report from Secretariat** *(10 minutes)*
   - Highlights from December 2017 Ministerial Meeting in Abu Dhabi
   - Review of Abu Dhabi Meeting Outcomes

   Richard Lynch, CSLF Secretariat

7. **Update from the CO_2GeoNet Association** *(15 minutes)*
   Ton Wildenborg, President, CO_2GeoNet Association

8. **Update from the IEA Greenhouse Gas R&D Programme** *(15 minutes)*
   James Craig, Senior Geologist, IEAGHG

9. **Update from the Global CCS Institute** *(15 minutes)*
   John Scowcroft, Executive Advisor – Europe, GCCSI

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

10:30-10:50 **Refreshment Break**
Sala Basaglia

10:50-12:20 **Continuation of Meeting**

11. **The ACT Project "ELEGANCY" – Synergies for Combining Hydrogen Production and CCS** *(30 minutes)*
    Svend Tollak Munkejord, Chief Scientist, SINTEF Energy Research, Norway

12. **Report on Hydrogen with CCS Task Force "Phase 0" Activities** *(15 minutes)*
    Lars Ingolf Eide, Task Force Chair, Norway

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

14. Report from Bioenergy with CCS Task Force *(15 minutes)*
Mark Ackiewicz, Task Force Chair, United States

15. 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

12:20-13:20 **Lunch**
Sala Basaglia

13:20-15:10 **Continuation of Meeting**

16. Review of Project Nominated for CSLF Recognition:
Enabling Onshore CO_2 Storage in Europe (ENOS) *(20 minutes)*
Marie Gastine, ENOS Coordinator, BRGM, France

17. Update on Mitsubishi's KM-CDR Process and Experience *(30 minutes)*
Takashi Kamijo, Chief Engineering Manager – CO_2-EOR Business Dept., Mitsubishi Heavy Industries, Japan

18. Results from CSLF-recognized Projects:
Fort Nelson Project and Zama Project *(30 minutes)*
James Sorensen, Principal Geologist, University of North Dakota Energy and Environmental Research Center (EERC), United States

19. Results from CSLF-recognized Project:
Norcem Carbon Capture Project *(30 minutes)*
Liv Bjerge, Sustainability Manager, HeidelbergCement, Norway

15:10-15:30 **Refreshment Break**
Sala Basaglia

15:30-17:45 **Continuation of Meeting**

20. Results from CSLF-recognized Project:
CO_2 Capture Project *(25 minutes)*
Mark Crombie, Program Manager – CO_2 Capture Project, BP, United Kingdom

21. Technical Group and CSLF Academic Task Force: Potential for Mutual Activities of Interest *(25 minutes)*
Sallie Greenberg, United States

22. Update from the Mission Innovation Carbon Capture Challenge *(15 minutes)*
Tidjani Niass, Saudi Aramco, Saudi Arabia

23. Possible New Technical Group Activities *(45 minutes)*
Åse Slagtern, Technical Group Chair, Norway
Paul Ramsak, Netherlands
Delegates

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

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

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

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

18:30 **CO_2 GeoNet Association reception begins**

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Minutes of the Technical Group Meeting

Abu Dhabi, United Arab Emirates
Monday, 04 December 2017

LIST OF ATTENDEES

Chair	Åse Slagtern (Norway)
Delegates	
Australia:	Andrew Barrett (*Vice Chair*), Max Watson
Canada:	Eddy Chui (*Vice Chair*), Mike Monea
China:	Jinfeng Ma
European Commission:	Jeroen Schuppers
France:	Didier Bonijoly, Dominique Copin
Italy:	Sergio Persoglia
Japan:	Ryozo Tanaka, Jiro Tanaka
Korea:	Chang-Keun Yi, Chong Kul Ryu
Mexico:	Jazmín Mota
Netherlands:	Harry Schreurs
Norway:	Lars Ingolf Eide, Espen Bernhard Kjærgård
Romania:	Constantin Sava, Anghel Sorin
Saudi Arabia:	Ammar Alshehri, Tidjani Niass
South Africa:	Noel Kamrajh (*Vice Chair*), Landi Themba
United Arab Emirates:	Arafat AlYafei, Fatma AlFalasi, Reshma Francy
United Kingdom:	Brian Allison
United States:	Mark Ackiewicz, Sallie Greenberg

Representatives of Allied Organizations

Global CCS Institute:	Jeff Erikson
IEA:	Tristan Stanley
IEAGHG:	Tim Dixon
CSLF Secretariat	Richard Lynch, Adam Wong

Invited Speakers

Australia:	Max Watson, CO2CRC
United Arab Emirates:	Fatima AlFoora AlShamsi, Ministry of Energy and Industry
United Kingdom:	Ceri Vincent, British Geological Survey (and) CO_2GeoNet
United States:	John Harju, University of North Dakota Energy and Environmental Technology Center
	Frank Morton, National Carbon Capture Center
	Chris Romans, MHI America

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Observers

Australia:	Timothy Sill*
Canada:	Goran Vlajnic
Japan:	Leandro Figueiredo
Korea:	Mi Hwa Kim*, Yi Kyun Kwon
Norway:	Arne Graue, Stig Svenningsen*
Saudi Arabia:	Feruih Alenuzey, Robert Dibble, Wolf Heidug, Pieter Smeets
United Arab Emirates:	Mohammad Abu Zahra, Sherry Adel Asaad, Ahmed AlHajaj, Hind Nuaman AlAli, Martin Jagger, Kasia Waker
United Kingdom:	Brendan Beck, Gardiner Hill
United States:	Damian Beauchamp, Bill Brown, Jarad Daniels*, Ed Steadman

* CSLF Policy Group delegate

1. Chairman's Welcome and Opening Remarks

The Chair of the Technical Group, Åse Slagtern, called the meeting to order and welcomed the delegates and observers to Abu Dhabi. Ms. Slagtern mentioned that this would be a busy meeting, with presentations on many topics of interest including presentations of results from three CSLF-recognized projects plus review of one new project which has been nominated for CSLF recognition. 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

Her Excellency Fatima Al Foora Al Shamsi, Assistant Undersecretary for Electricity and Future Energy Affairs at the United Arab Emirates' Ministry of Energy and Industry, welcomed the meeting attendees to Abu Dhabi. Dr. Al Shamsi stated that the 2017 CSLF Mid-Year meeting, also in Abu Dhabi, was an excellent example of how the collective knowledge of world class experts in the field of carbon capture and storage (CCS) can lead to progress. Three projects were recognized by the CSLF at that meeting, including the Al Reyadah Carbon Capture, Utilization and Storage (CCUS) Project which captures industrially-produced carbon dioxide (CO_2) from the Emirates Steel facility and delivers it to an ADNOC oil field where it is utilized for enhanced oil recovery. For the energy sector of the United Arab Emirates, the Al Reyadah project shows how partnerships and a bold vision can deliver success in the field of carbon capture, utilization and storage. Dr. Al Shamsi closed her welcoming speech by thanking all organizations such as the IEAGHG and Global CCS Institute as well as the task forces under the CSLF for their continuing efforts on advancing various aspects of CCS and looked forward to productive discussions and positive outcomes from this meeting.

3. Introduction of Delegates

Technical Group delegates present for the meeting introduced themselves. Seventeen of the twenty-six CSLF Members were represented. Observers from nine countries were also present.

4. Adoption of Agenda

The Agenda was adopted with no changes. Presentations by delegates from Romania and China were included in the “General Discussion” agenda item.

5. Approval of Minutes from 2017 Mid-Year Meeting

The Minutes from the May 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 May 2017 CSLF Mid-Year Meeting. This was a five-day event, including a site visit to the Al Reyadah CCUS Project and a technical workshop themed on “Carbon Utilization Challenges and Opportunities” and “Spotlight on Carbon Capture”. Presentations from all meetings and the workshop are online at the CSLF website.

Mr. Lynch stated that there were several key outcomes from the May 2017 Technical Group meeting. First and foremost, the Al Reyadah CCUS Project, the National Risk Assessment Partnership, and the Carbon Capture Simulation Initiative / Carbon Capture Simulation for Industry Impact were all recommended by the Technical Group to the Policy Group for CSLF recognition. Additionally, there were reports from four existing Technical Group task forces and formation of a new working group, led by Norway, to evaluate existing and new ideas for possible future Technical Group actions. Finally, the CSLF Technology Roadmap (TRM) working group reported that a mostly-final version of the 2017 TRM had been completed and was undergoing final review.

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

Tim Dixon, the Technical Programme Manager for the IEAGHG, gave a concise 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, the seven 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

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conferences, its annual International CCS Summer School, peer reviews with other organizations, activity in international regulatory organizations such as the UNFCCC, the ISO TC265, and the London Convention, and collaboration with other organizations, including the CSLF.

Mr. Dixon mentioned that since 2008 the IEAGHG and CSLF Technical Group have enjoyed a mutually beneficial relationship which allows each organization to cooperatively participate in the other's activities. This has included mutual representation of each at CSLF Technical Group and IEAGHG Executive Committee (ExCo) meetings, and also the opportunity for the Technical Group to propose studies to be undertaken by the IEAGHG. These, along with proposals from IEAGHG ExCo members, go through a selection process at semiannual ExCo meetings. So far there have been 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.

Mr. Dixon concluded his presentation with a list of reports recently published, reports in progress to be published, studies underway, and studies awaiting start. Mr. Dixon also briefly described IEAGHG events, including its webinar series and next year's GHGT conference.

8. Update on the Global Status of CCS

Jeff Erikson, General Manager for the Americas at the Global Carbon Capture and Storage Institute (GCCSI), gave a short presentation about the global status of CCS. Since the early 1970s, more than 200 million tonnes of CO_2 have been captured and stored in deep underground geologic formations. Overall, capture technologies are now widely utilized at large-scale globally, with costs declining as new facilities come online and technologies further mature. As of 2017 there are 17 large-scale CCS projects throughout the world which are in operation, capturing more than 30 million tonnes CO_2 per year annually. An additional four large-scale projects are scheduled to come online in 2018, and will capture an additional 6 million tonnes CO_2 per year. Between December 2016 and December 2017 there were start-ups of two large-scale facilities in the United States (the Petra Nova Project and the Archer Daniels Midland Project). In Norway, the offshore Sleipner and Snøhvit facilities have surpassed 20 million tonnes of CO_2 captured and stored. In Canada the Quest Project has achieved more than 2 million tonnes of CO_2 captured and stored since its 2015 start-up and the SaskPower Boundary Dam Project will soon reach that same milestone. Additionally, two other western hemisphere large-scale projects (the industrial Air Products Project in the United States and the offshore natural gas processing Santos Basin Project in Brazil) have each captured more than 4 million tonnes of CO_2 since their start-ups.

Mr. Erikson stated that three other large-scale projects, in China, Australia and Canada, are scheduled to come online in 2018, with the Gorgon Project in Australia having a capacity of up to 4 million tonnes of CO_2 captured and stored annually. And besides all these very large-scale activities, there are many somewhat smaller facilities throughout the world, including the Tomakomai CCS Project in Japan, which are conducting important technology verification activities on various aspects of CO_2 capture, monitoring, and verification of storage. In closing his presentation, Mr. Erikson stated that the GCCSI has published an extensive report on the global status of CCS and it is available for viewing at its website.

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9. Update from CO_2GeoNet

The Chair of the CO_2GeoNet Executive Committee, Ceri Vincent, gave a short presentation about the CO_2 GeoNet Association 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. There are now 28 members from 21 countries, including industry, academia, and research institutes. As an independent and multidisciplinary scientific body, CO_2 GeoNet has an important role in building trust in CO_2 geological storage and supporting large-scale implementation of CCS.

Ms. Vincent stated that CO_2GeoNet has four categories of activities: joint research, scientific advice, training, and information / communication. An example of a joint research activity is the Enabling Onshore Storage (ENOS) Project, which began in 2016 and will run through 2020. ENOS currently has 29 partners from 17 countries, with five field laboratories / pilot sites. The overall goal of the project is to prepare a favorable environment for onshore CO_2 storage in Europe.

Ms. Vincent also stated that CO_2GeoNet is very active in outreach activities, exemplified by its being selected (along with the U.K. CCS Association) as the CSLF's regional stakeholder 'champion' for Europe and has contributed to the CSLF's overall stakeholder engagement strategy. It is also involved in training activities via educational programs and is building a framework for a Masters-level graduate school course for CCS. Ms. Vincent concluded her presentation by mentioning that CO_2GeoNet holds an annual Open Forum; the theme of the 2017 Forum was "Driving CCS towards implementation" and included the knowledge-sharing workshop "Bringing CCS into new regions".

10. Report on Mission Innovation Experts Group Workshop

The Co-Chair of Mission Innovation's Carbon Capture Innovation Challenge, Tidjani Niass, gave a short presentation about Mission Innovation and the Innovation Challenge. 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 for the participating countries to double their clean energy R&D investment over five years, while encouraging greater levels of private sector investment in transformative clean energy technologies. To that end, an invitation-only "Experts Workshop", as part of the Carbon Capture Innovation Challenge (CCIC), was held in the United States in September 2017.

Dr. Niass stated that the overall objective for the CCIC is to develop a route to near-zero CO_2 emissions from power plants and carbon intensive industries. This would involve identifying and prioritizing breakthrough CCUS technologies, developing pathways to close RD&D gaps, recommending multilateral collaboration mechanisms, and driving down the cost of CCUS through innovation. The Experts Workshop, which was co-chaired by the United States and Saudi Arabia, 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. Outcomes included creation of an international consensus on the most critical scientific challenges in these areas as well as crosscutting topics and establishing internationally agreed priority research directions such as tailoring material properties to enable CCUS. Next steps will be publication of the Workshop report (scheduled for early 2018), developing and implementing collaboration mechanisms, fostering engagement with industry, and preparing for the upcoming 3rd Mission Innovation Ministerial.

Ensuing discussion brought forth several ideas for Mission Innovation and the CCIC to consider. Jeroen Schuppers stated that the European Union's "Horizon 2020" research and innovation programme contains a number of topics which are open to participation from Mission Innovation member countries. Ryozo Tanaka inquired how the next steps described in the presentation would be addressed. Dr. Niass replied that there are not yet any definitive plans for doing so, but the CCIC Steering Committee would be discussing this in its teleconferences and in a meeting to be held in early 2018 in Ottawa, Canada. Brian Allison stated that the European Research Area Network's Accelerating CCS Technologies (ACT) initiative, which has so far selected eight transnational projects representing a combined funding of €38 million, is very interested in having projects and activities identified under the Carbon Capture Innovative Challenge respond to future ACT calls for project proposals. Mr. Allison also stated that while the Experts Group Workshop is a good start, he hoped that the Carbon Capture Innovative Challenge would soon take the next step beyond that. Dr. Niass agreed, and stated that the ACT platform might be a good place to start but does want more collaboration opportunities than just that.

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

The PIRT Chair, Andrew Barrett, gave a short presentation which summarized PIRT activities and the previous day's meeting. The PIRT is currently involved in three main activities: reviewing projects nominated for CSLF recognition, updating the CSLF Technology Roadmap (TRM), and finding ways to better engage sponsors of CSLF-recognized projects. Mr. Barrett reported that there were three main outcomes from the meeting:

- The PIRT has recommended approval by the Technical Group for the CO2CRC Otway Project Stage 3 to become a CSLF-recognized project.
- The 2017 TRM has been completed and launched. It should be noted that this is a beginning and not an end in itself, and there should be actions taken by the CSLF to ensure that the TRM remains a living and useful document. To that end, a PIRT working group was organized to explore and suggest approaches for tracking follow-up and progress of the TRM recommendations. The group will also explore the feasibility of utilizing expertise and learnings from CSLF-recognized projects as input to future editions of the TRM.
- The PIRT's Terms of Reference document was reviewed and updated. Significant changes included updating the methodology for how the PIRT approves projects proposed for CSLF recognition.

Mr. Barrett stated that the PIRT meeting had also featured a preview of an item on the Technical Group's current meeting agenda on evaluating new ideas for Technical Group future actions. The discussion in the PIRT meeting had helped clarify thinking about how to proceed in this area, and would be summarized during the agenda item on that topic later in the current Technical Group meeting.

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12. Preview of 2017 CSLF Technology Roadmap (TRM)

The Chair of the TRM working group, Andrew Barrett, and the Editor of the TRM, Lars Ingolf Eide, gave a short presentation about the 2017 TRM. The TRM working group had been formed at the 2015 Technical Group meeting in Riyadh with the mandate to produce a new TRM in time for the 2017 CSLF Ministerial Meeting. The process chosen for the rewrite was to use the 2013 TRM as a basis and refresh its content as needed. Editorial responsibility for updating the document was shared among the working group, with Mr. Eide the editor-in-chief. The Working Group was chaired by Australia with representation from Norway, Canada, South Africa, the United Kingdom, the United States, the IEAGHG, and the CSLF Secretariat. In addition, there have been contributions from several international experts on CCS.

Mr. Barrett briefly described the main changes from the 2013 TRM:

- For the purposes of the 2017 TRM, CCUS has been defined as a subset of CCS.
- New time horizons were used for medium- and long-term recommendations and targets (2025 and 2035 respectively, instead of the previous TRM's target dates of 2030 and 2050).
- The "Background" chapter was revised to reflect COP21 targets, and quantitative targets that meet the IEA 2 ºC scenario were used for CO_2 sequestration.
- There is a new section on non-technical measures such as regulations.
- There is now less detail concerning specific CO_2 capture technology types and fundamentals, and more emphasis on industrial and biomass CCS.
- There is a new section on CO_2 capture on hydrogen as a mechanism to decarbonize industry.
- There is more emphasis on development of a "clusters and hubs" approach toward CCS, and also on ship transport of CO_2.
- Recent CO_2 storage projects and activities have been referenced, and description has been updated and expended about various aspects of CO_2 utilization.
- There is expanded and updated text, particularly on offshore CO_2-Enhanced Oil Recovery (EOR) and other CO_2 utilization options. A description of barriers to CO_2 utilization was also added.
- There are identified actions to meet technology needs throughout the CCS chain.

Mr. Barrett then yielded to Mr. Eide who stated the main findings of the 2017 TRM are that CCUS works in power and industrial settings. However, the coming years is a critical period for CCS and therefore a sense of urgency must emerge which will drive actions. Substantial and perhaps unprecedented investment in CCS and other low carbon technologies is needed to achieve the targets of the Paris Agreement, and the main barriers to implementation are inadequate government investment and policy support initiatives, challenging project economics, and uncertainties / risks that stifle private sector investment. Other significant findings are that rapid development of CCS is critical in the industry and power sectors, especially in 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, while costs and implementation risks for CCS can be reduced by developing industrial clusters and CO_2 transport / storage hubs. Finally, members of the CSLF consider it critical that public-private partnerships form to facilitate cost-reductions and accelerated implementation of CCS.

Mr. Eide then described the priority recommendations made by the 2017 TRM. Governments and industry must collaborate to ensure that CCS contributes its share to the Paris Agreement's targets by implementing sufficient large-scale projects in order to achieve the following:

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

To that 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 down costs 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.

Mr. Eide concluded the presentation by stating the takeaway message that is being provided to the Ministers: **Governments have a critical role in accelerating the deployment of CCS**.

13. Report from the Offshore CO_2-EOR Task Force

Task Force Chair Lars Ingolf Eide gave a brief update on the task force, which was established at the November 2015 meeting in Riyadh. The purpose of the task force was to highlight differences and issues between onshore and offshore CO_2-EOR as well as offshore CO_2-EOR and pure offshore CO_2 storage. The task force also highlighted any technical solutions that benefit both pure offshore CO_2 storage and offshore CO_2-EOR. Task force members included Norway (as chair), Brazil, Canada, Mexico, the United States, and the IEAGHG. The methodology of the task force was to examine existing, although not necessarily published, information.

Mr. Eide stated that a draft of the task force's final report had been completed and previewed at the 2017 CSLF Mid-Year Meeting. The contents of the report includes chapters on the basics of offshore CO_2-EOR, insights from the Brazilian "Lula" off-shore CO_2-EOR project, approaches and emerging technical solutions toward enabling offshore CO_2-EOR, description of emerging technical solutions for offshore CO_2-EOR and offshore CO_2 storage, description of potential CO_2 supply chain issues, issues involved with monitoring and verification of storage, description of regulatory requirements for offshore CO_2 utilization and storage, a summary of barriers that exist for implementing offshore CO_2-EOR projects, and recommendations for overcoming those barriers.

Following Mr. Eide's presentation there was consensus by the Technical Group to accept the final report. Mr. Eide then stated that the task force was hereby disbanded.

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. The focus of the task force is to identify the overall commercial status for BECCS, technology options and pathways, biomass resource assessments, emissions profiles, and economic analyses. The draft report identifies various commercial projects in operation, market drivers, and barriers to large-scale BECCS demonstration and deployment. Mr. Ackiewicz also presented a set of findings and recommendations from the task force on the topics of biomass feedstocks, technology, analyses, outreach / communications, and financing. The task force's final report was drafted by the United States Department of Energy, the IEAGHG, the Center for Carbon Removal, and the International Research Institute of Stavanger, and included review and contributions from CO_2GeoNet, the Research Council of Norway, SINTEF, and Shell. Mr. Ackiewicz stated that a draft of the task force's final report has been completed and is in final review.

15. Report from the Improved Pore Space Utilisation Task Force

Task Force Co-Chair Brian Allison 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. 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. Pore space utilisation related to EOR and reservoir stimulation were not considered by the task force as these would greatly increase the level of effort and require expertise beyond what exists with task force participants.

Mr. Allison stated that the task force's final report would include six topics related to pore space utilisation: regulatory considerations, technology & process review, microbubble injection, saturated water & geothermal energy production, compositional & temperature swing injection, and ranked technique effectiveness. Work is complete on all topics except for the technology & progress review and ranked technique effectiveness sections, which are still under review. Mr. Allison concluded his presentation by stating that the task force timeline now shows the final report review cycle to be complete by mid-March 2018, after which it will be sent to task force members for a final check and then to the entirety of the Technical Group. The final report will be presented to the Technical Group at its next meeting.

16. Report from the CCS for Industries Task Force

Task Force Chair Didier Bonijoly asked Dominique Copin to present the task force report. This task force was established at the October 2016 meeting in Tokyo with a mandate to investigate the opportunities and issues for CCUS in the industrial sector and show what the role of CCUS could be as a lower-carbon strategy for CO_2-emitting industries. The task force consists of members from France's Club CO_2, with additional commitment from Canada, Norway, Saudi Arabia, the United Arab Emirates, and the

GCCSI. Mr. Copin mentioned that almost all industrial sectors are engaged in this activity either via a company in one of those sectors or a professional organization. Relevant issues being examined include: why CCUS 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.

Mr. Copin stated that the task force's time line calls for it to receive and review contributions to its final report through the end of January 2018. The first draft of the report will be done in March 2018 and will be presented to the Technical Group at its next meeting. A review cycle for the draft report will produce a finalized report by about mid-2018. During ensuing discussion, Tristan Stanley mentioned that the IEA is just starting on a new roadmap for decarbonizing the iron and steel industry, and would be willing to share results with the task force.

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

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.

The working group's chairman, Lars Ingolf Eide, 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. There are currently four active task forces besides the PIRT: Improved Pore Space Utilization (co-chaired by Australia and the United Kingdom), Bioenergy with CCS (chaired by the United States), Industrial CCS (chaired by France), and Offshore CO_2-EOR (chaired by Norway which completed its activities in 2017). Mr. Eide stated that there are eleven 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. Additionally, there have been eleven other actions, which were completed between 2006 and 2015 and have resulted in task force final reports.

Mr. Eide then described the process for developing and prioritizing a long list of future potential actions. In all, 24 potential new topics were included – eleven unaddressed items from 2015, eleven past task force topics (for possible updates), and two new proposals. The members of the working group then participated in a preference poll, which resulted in 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

Mr. Eide stated that for the proposed action on Hydrogen as a Tool to Decarbonize Industries, the working group had come up with several sub-topics that could be addressed: hydrogen production and use; hydrogen with CCS, synergies with renewables, life cycle costs and carbon footprint; and hydrogen value chain. Additionally, there are several existing activities and programs – in Europe, Japan, and the United States as well as with multinational energy companies such as Statoil, Gasunie, and Vattenfall Nuon – which could be mapped in a "Phase 0" of a new Technical Group task force.

Ensuing discussion led to the formation of the new Task Force on Hydrogen with CCS which would conduct “Phase 0” activities in time for the next Technical Group meeting, where a decision would be made on whether or not to continue the task force. For this zeroth phase, the task force will be led by Norway (Lars Ingolf Eide), with participation / contributions by Australia (Max Watson), Canada (Eddy Chui), France (Didier Bonijoly), Japan (Ryozo Tanaka), the Netherlands (Harry Schreurs), Saudi Arabia (Ammar Alshehri), the United Arab Emirates (Arafat AlYafei), the United Kingdom (Brian Allison), the IEAGHG (Tim Dixon), and the CSLF Secretariat (Richard Lynch).

Additionally, Harry Schreurs gave some information on the CO_2 Capture by Mineralization proposed activity, after which several other delegates expressed interest. Mr. Schreurs stated that he would investigate the possibility for the Netherlands to lead a task force on this topic and that he would present a detailed proposal at the next Technical Group meeting.

18. Report on Global CCS Symposium

Mike Monea, President and CEO of the International CCS Knowledge Centre (ICCSKC), provided a short presentation on the October 2017 Global CCS Symposium which was held in Regina, Saskatchewan, Canada and hosted by the ICCSKC. Mr. Monea stated that the ICCSKC was established as a non-profit organization in 2016 with a mandate to advance the understanding and use of CCS as a means of managing CO_2 emissions. Its focus is on facilitating the sharing of data, information, and lessons learned from SaskPower’s Boundary Dam CCS Project and other large-scale CCS projects in other parts of the world.

Mr. Monea stated that the theme of the three-day October 2017 Symposium was “Advancing a Path Forward” with an emphasis on positive and noteworthy stories of CCS projects that are in operation as provided by representatives of those projects. There were 150 representatives from 16 countries in attendance, with sessions themed on “Large-Scale CCS Development: It Can be Done”, “Key Economic Considerations – Building on Experience for the Future”, and “Optimization – An Insider’s Look” as well as other sessions about advancements in CO_2 storage, CCS in a Paris world, exploring enabling policies for CCUS development, and CCUS on industrial sources. Mr. Monea closed his presentation by providing some of the key takeaways from the symposium: the costs of CCS are coming down; CCS allows us to transition out of fossil fuels in a clean way; EOR is a tool to spur development but policies must go further; CO_2 conversion sounds good but may take more energy; and small scale CCUS is not enough – more large-scale demonstrations are needed.

19. Update on International Test Center Network (ITCN)

Frank Morton, Director of Technology at the National Carbon Capture Center (NCCC) in the United States, gave a short presentation about the ITCN and its collaborative activities. The ITCN was launched in 2013 to accelerate CCS technology development. Its main function is to facilitate knowledge sharing of operational experience and non-confidential information for CO_2 capture technologies, in terms of facility operations, facility funding, safety, and analytical techniques. Among the objectives of the ITCN are increasing insight and awareness of different technologies that may reduce risks and increase investments in CO_2 capture technologies and enhancing public awareness and acceptance of the technologies involved. The ITCN will also work with technology developers as appropriate on scale-up testing of their technologies.

Mr. Morton stated that criteria for a test facility's membership in the network is that the facility must be operating on real flue gas (i.e., be connected to a power plant or industrial plant), it must have the intent of being neutral in any technology decisions, and it must be willing to share information and receive visitors. The ITCN currently has 13 members (including the NCCC) representing large and smaller-scale CO_2 capture facilities on four continents, and in the four years it has been in existence there have been numerous collaborations between its members. Mr. Morton concluded his presentation by briefly describing future activities of the ITCN. These include sharing information with China, which will be operating two test CO_2 capture facilities, and with India, which is interested in CO_2-EOR.

20. Results from CSLF-recognized Project: Rotterdam Opslag en Afvang Demonstratieproject (ROAD)

Harry Schreurs provided a retrospective overview of the recently-canceled ROAD project. ROAD had been recognized by the CSLF at its 2009 Ministerial Meeting in London, but its ten-year life was ended by insurmountable funding issues. However, there were many valuable lessons learned, which were described by Mr. Schreurs. Concerning CO_2 capture, there were sufficient proven technologies available where there was confidence that any engineering problems could be solved – in other words, the technology is available and will work. For CO_2 transport there were some technical uncertainties such as managing two-phase flow behavior but CO_2 pipelines are by now conventional technology which will work. CO_2 storage technologies are also available and have been proven to work, but storage regulations (especially issues concerning liability) are not yet to the point where a large-scale project is easily do-able.

Mr. Schreurs stated that while the lack of a regulatory regime was a potential show-stopper, the actual reason that ROAD failed (which also applies to other failed large-scale CCS projects in Europe) was because nobody was prepared to pay for it – ROAD was a project without a customer or a constituency. Industrial partners did not have a business case and public funders did not have sufficient public and political support. For the latter, CCS had been perceived in the Netherlands as being in competition with investments in renewables and as an optional measure of last resort in an attempt to keep coal-fueled power generation relevant. Mr. Schreurs closed his presentation by stating the key lesson learnt from ROAD: Government has to fund CCS, at least for the initial round of demonstrations, because there is not yet any other customer. To succeed, projects must be designed and operated to maximize long-term Government support.

21. Review and Approval of Project Proposed for CSLF-Recognition: CO2CRC Otway Project Stage 3

(nominated by the Australia [lead], Canada, France, Mexico, Norway, Saudi Arabia, and the United Kingdom)

Max Watson, representing project sponsor CO2CRC, gave an overview presentation about the Otway Stage 3 project. 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.

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

22. Results from CSLF-recognized Project: Plant Barry Integrated CCS Project

Chris Romans, representing technology provider MHI Americas, provided a brief summary of the CO_2 capture aspects for the now-completed Plant Barry Integrated CCS Project. The project utilized MHI's proprietary KM CDR Process for capture of CO_2. Mr. Romans stated that the Plant Barry Project, located near Mobile, Alabama in the United States and operated jointly by The Southern Company and MHI, was an important large pilot project which helped prove commercial viability of MHI's carbon capture technology with coal-fueled flue gas. A slipstream provided flue gas equivalent to 25 megawatts of power production and some of the captured CO_2 was transported by a 19-kilometer pipeline to the injection site, where it was stored in deep saline formation approximately 3 kilometers below ground. In all, more than 200,000 tonnes of CO_2 was captured in the duration of the project, with 115,000 tonnes transported and stored. Mr. Romans closed his presentation by stating that the experience gained during this project resulted in scale-up of the CO_2 capture technology for use in the W.A. Parish "Petra Nova" demonstration project in Texas, which is capturing 4,776 tonnes of CO_2 per day.

23. Results from CSLF-recognized Project: Lacq Integrated CCS Project

Dominique Copin, representing project sponsor Total, provided a brief summary of the now-completed Lacq Integrated CCS Project. This was an intermediate-scale project based on natural gas-fueled oxyfuel combustion which tested and demonstrated an entire integrated CCS process throughout the complete industrial chain, from emissions source to underground storage in a depleted gas field. The project captured and stored a total of 51,000 tonnes of CO_2 from an oxyfuel gas-fired industrial boiler in the Lacq industrial complex in southwestern France. The goal was to demonstrate the technical feasibility and reliability of the integrated process, including the oxyfuel boiler, 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. Mr. Copin stated that the outcome from the CO_2 capture component of the project was that a sufficient amount of data was obtained to design a full-scale 200-megawatt oxyfuel boiler. Results from the CO_2 storage component included characterization of a depleted gas reservoir as a CO_2 storage site as well as a demonstration of the ability to monitor the integrity and environmental impact of such a CO_2 storage site. Mr. Copin also stated that the Lacq Project's public outreach campaign was very successful in engaging the populace in the vicinity of the project. In that regard, the project published a brochure in 2014 that summarized its stakeholder outreach activities and has also created a "lessons learned" document that is available at the GCCSI website.

24. Results from CSLF-recognized Project: Uthmaniyah CO_2-EOR Demonstration Project

Ammar Alshehri, representing project sponsor Saudi Aramco, provided a brief update on the progress and activities for the Uthmaniyah CO_2-EOR Demonstration Project. This is a large-scale demonstration which is capturing and utilizing approximately 800,000 tonnes of CO_2 per year. It was highlighted that Saudi Aramco does not need EOR to meet the global energy demand; the project is a long-term resource planning strategy and an approach to protect the environment. Dr. Alshehri stated that the Uthmaniyah project is part of Saudi Aramco's overall carbon management activities and that Saudi Aramco has developed a technology roadmap that includes capturing CO_2 from fixed and mobile sources, CO_2 conversion into industrial applications, and CO_2 sequestration as focus areas in addition to CO_2-EOR. The Uthmaniyah project captures CO_2 from natural gas processing operations and includes an 85-kilometer pipeline to transport the CO_2 to the injection site. Overall, approximately 2,000 tonnes of CO_2 per day are being injected with about 80% of the CO_2 being retained in the reservoir.

A key feature of the project is its monitoring program, which includes seismic monitoring (via an array of 1,000 sensors), cross-well electromagnetic surveillance for plume tracking, borehole / surface gravity methods for plume tracking and leak detection, and inter-well tracer tests to accurately determine the CO_2 flow paths. Monitoring parameters include the volume of the sequestered CO_2, plume evolution, and CO_2 migration and containment. This monitoring is being carried out continuously with data routed through a field center. Dr. Alshehri concluded his presentation by mentioning that this project is only a test to determine the feasibility of CO_2-EOR in Saudi Arabia, as there will not be a need for widespread use of this technology for probably several decades.

25. Regional Evaluation of the Complete CCS Value Chain

John Harju, Vice President for Strategic Partnerships at the University of North Dakota's Energy and Environmental Research Center (EERC), gave a short presentation, which provided an overview of the synergies that exist between regional coal and petroleum producers via use of CCUS. A project team headed by EERC is conducting a quantitative evaluation of the technical and economic impacts of the carbon value chain in North Dakota, which is the 6^{th} greatest coal producer and the 2^{nd} greatest petroleum producer in the United States. CCUS in North Dakota is therefore key for assuring that energy can be provided in a clean, affordable and reliable manner. Mr. Harju stated that EERC's quantitative evaluation has been comprehensive, including upstream activities (lignite mining and power generation), CO_2 transportation aspects, and downstream activities (CO_2-EOR and associated CO_2 storage). The high-level economic impact of CCUS in North Dakota is a positive effect on the regional economy and tax revenues. CCUS would result in a continuous and affordable supply of CO_2 which would greatly increase the amount of petroleum that can be produced. Mr. Harju stated that the EERC evaluation is examining ways to capitalize on the regional synergies, and this would include development of potential business models which factor in process and demand for coal, oil and electricity, and also examining the effect of current and possible future incentives at both he state and federal level. The effect of the increasing amount of energy being obtained from renewables is also being considered. Mr. Harju closed his presentation by pictorially indicating that only a small fraction of shale oil in North Dakota is currently economically recoverable, and that better understanding the techno-economic impacts of linking North Dakota lignite with CO_2-EOR will lead to a more robust energy industry in the state.

26. Overview and Status of the Carbon Storage Data Consortium

Sallie Greenberg provided a brief update on the Carbon Storage Data Consortium (CSDC), which had been created in 2016 following discussions in 2015 between United States and Norway researchers. The CSDC underpins another CSLF initiative, the Large-

Scale Saline Storage Project Network, whose formation had been announced in November 2015 at the 6th CSLF Ministerial Meeting. Current membership of the CSDC includes two organizations from the United States, five from Norway, and the IEAGHG. The overall objectives of the CSDC are to accelerate improved understanding and minimize uncertainties associated with storage of CO_2, to establish and operate a platform for sharing reference datasets from pioneering CO_2 storage projects, to provide to data owners a simple, standard and low cost solution for making data available to research organizations worldwide, and to open an international network for data and knowledge exchange. The goal is to make initial CSDC datasets available in the 2018/2019 timeframe.

Dr. Greenberg described how the CSDC data sharing network could work. Sponsoring organizations involved with geologic CO_2 storage would provide information to the CSDC project team and steering committee, which would process/screen the data and make it available to a broader user community via a data-hub provider. Survey results from 50 stakeholder respondents have clarified how the CSDC should move forward: ranking of datasets is very important as most stakeholders are users and not providers of datasets, but few respondents appeared open to paying a fee in order to participate. As a result, the CSDC is currently exploring alternative technical solutions for data sharing, ranging from the simple, low-cost-but-low-flexibility to the complex, higher cost-and-full-flexibility approaches. Dr. Greenberg concluded her presentation by stating that the CSDC has been awarded funding from both the United States Department of Energy's National Energy Technology Laboratory and Norway's CLIMIT program. However, it is important to secure additional international commitments to ensure its long-term operations. To that end, the CSDC is seeking to expand its membership by inviting organizations in other countries besides the United States and Norway to join.

27. Outcomes and Messages from 2nd International Workshop on Offshore CO_2 Storage

Tim Dixon provided a brief update on results and outcomes from the 2nd International Workshop on Offshore Geologic CO_2 Storage, which was held in June 2017 and hosted by Lamar University, in Beaumont, Texas in the United States. Mr. Dixon stated that the workshop had been organized by the University of Texas's Bureau of Economic Geology in collaboration with the IEAGHG and the South Africa National Energy Development Institute (SANEDI). One of the purposes of the workshop was to facilitate sharing of knowledge and experiences among those who are doing offshore CO_2 storage and those who have an interest in doing so at some point in the future. Mr. Dixon stated that the Workshop was a good capacity building event and overall there were 50 attendees representing nine countries.

Mr. Dixon stated that the aim of the workshop was to build on recommendations and topics raised during the 1st Workshop in order to take offshore storage forward. In particular, there were technical "deep dives" into several key topics: how to find storage offshore; technical aspects and experiences of offshore monitoring; offshore CO_2-EOR; infrastructure developments and decisions; and developments in offshore storage assessments in the Gulf of Mexico. Outcomes from the workshop were a set of conclusions and recommendations, relevant to areas such as environmental monitoring, risk mitigation, cost management, and infrastructure, as well as their policy implications. Mr. Dixon closed his presentation by mentioning that a report on the workshop has been completed and has been posted to the IEAGHG website.

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28. Update on Activities of the ISO/TC265

Sallie Greenberg provided a brief update about the International Organization for Standardization (ISO) TC265 technical committee. The overall objective of TC265 is to prepare standards for the design, construction, operation and related activities in the field of CO_2 capture, transportation and geologic storage. The TC265 consists of six working groups focused on different aspects of CCS, each with proposed standards working their way through review and approval procedures. Concerning the TC265 and the CSLF, there has been significant interest by the TC265 in the CSLF's TRM and its recently-published Regulatory Task Force Case Study Report. Dr. Greenberg reported that at the most recent meeting of TC265 was in late November 2017, in Sydney, Australia, there was discussion about a possible greater liaison by the TC265 with the CSLF which might include topics such as a stakeholder engagement standard. At that meeting, Dr. Greenberg gave a short presentation about the CSLF that included information on its objectives, organization, previous meetings, and activities of CSLF Technical Group task forces. During ensuing discussion, the Technical Group reached consensus that Dr. Greenberg would be the Technical Group's liaison to the TC265.

29. Preview of Technical Group Presentation at Ministerial Conference

Technical Group Chair Åse Slagtern previewed her "Messages and Recommendations from the CSLF Technical Group" presentation to the upcoming Conference of CSLF Ministers. The presentation mostly summarized recommendations from the TRM (listed above in Item 12), but also noted that barriers are in place that are preventing the widespread utilization of CCS. Ms. Slagtern concluded her presentation by emphasizing the Technical Group's "takeaway message" to the Ministers: **Governments have a critical role in accelerating the deployment of CCS**.

30. Update on Future CSLF Meetings

Richard Lynch stated that there was nothing yet to report about the 2018 Mid-Year Meeting. Policy Group Chair Jarad Daniels stated that he would be interested in hearing from any CSLF Member who would like to host the 2018 Mid-Year Meeting or one of the 2019 meetings. Max Watson re-affirmed that Australia will be hosting the 2018 Annual Meeting in October 2018 on a week adjacent to the week of the IEAGHG's GHGT conference. Additional details would also be forthcoming soon.

31. Open Discussion and New Business

Two previously unscheduled presentations were made during this item. Constantin Sava, Senior Scientist at Romania's National Institute of Marine Geology and Geoecology (GeoEcoMar), provided information about the Accelerating Low carbon Industrial Growth through CCS (ALIGN) project, which is addressing specific issues across the CCUS chain using results from projects in the United Kingdom, the Netherlands, Germany, and Norway. There are currently 31 partner organizations and the project has so far secured approximately €15 million in funding. The project will run through 2020 and consists of six work packages: CO_2 capture, CO_2 Transport, CO_2 storage, CO_2 Re-Use, Industrial Clusters, and Societal Issues. Dr. Sava also made a brief presentation about the Enhanced Oil Recovery with Storage (ECO-BASE) Project, which is being managed by the International Research Institute of Stavanger, Norway and in which GeoEcoMar is a project partner. ECO-BASE is attempting to establish a business case for CO_2-EOR in southeastern Europe, with a first step of developing detailed and integrated roadmaps for CCUS in that part of Europe. Expected milestones include accomplishing the mapping of existing CO_2 sources and possible CO_2 sinks while determining what the most promising opportunities for CO2-EOR are in terms of developing a business case. There would also be capacity building opportunities for the region with outreach and CCUS-related instructional courses.

Jinfeng Ma, representing the National & Local Joint Engineering Research Center of Carbon Capture and Storage Technology of Northwest University in Xi'an, China, gave a short presentation that described China's CCUS progress and deployment. Prof. Ma stated that the Chinese government has adopted several incentive policies to promote the demonstration of CCS projects, but the most important government plans are an energy technology innovation action plan by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) in 2016, and the 13th Five-Year Plan for National Scientific and Technological Innovation by the Ministry of Science and Technology (MOST) in 2016. NDRC and the Asian Development Bank (ADB) have also created a roadmap for CCS demonstration and deployment in China. ADB has also provided support to Northwest University for a team of experts to design a comprehensive strategy for China to promote CCS. Prof. Ma also provided information about planned and operational CCS projects in China, of which there are many. One of these is the Jingbian CCS Project, which was recognized by the CSLF in 2015. Prof. Ma stated that the measuring, monitoring and verification component of this pilot-scale project includes research and study of parameters such as efficiency of geochemistry and reservoir simulation, CO_2 injection strategy, confirmation of wellbore integrity and CO_2 plume migration, confirmation of caprock integrity, and advanced online monitoring techniques.

32. Closing Remarks / Adjourn

Ms. Slagtern thanked the meeting host United Arab Emirates Ministry of Energy and Industry, the Secretariat for its support, and the delegates for their active participation. She then adjourned the meeting.

Summary of Meeting Outcomes

- The CO2CRC Otway Project Stage 3 is recommended by the Technical Group to the Policy Group for CSLF recognition.
- The 2017 TRM has been completed and launched.
- With the issuance of its final report, the Offshore CO_2-EOR Task Force has now completed its activities and has disbanded.
- The BECCS Task Force and the Improved Pore Space Utilisation Task Force will present their final reports to the Technical Group at its next meeting.
- The CCS for Industries Task Force will present a draft report at the next Technical Group meeting.
- A new Task Force on Hydrogen with CCS has been formed, with initial "Phase 0" activities reviewing existing activities and programs in Europe, Japan, and the United States as well as those by multinational energy companies. Participants in this initial phase include Norway (lead), Australia, Canada, France, Japan, the Netherlands, Saudi Arabia, the United Arab Emirates, the United Kingdom, the IEAGHG, and the CSLF Secretariat.

- A detailed proposal on forming a new task force on CO_2 Capture by Mineralization will be presented by the Netherlands at the next Technical Group meeting.
- United States delegate Sallie Greenberg will be the Technical Group's liaison with the ISO TC265 technical committee on CO_2 capture, transportation and geologic storage.

Carbon Sequestration Leadership Forum

www.cslforum.org

Technical Summary of Bioenergy Carbon Capture and Storage (BECCS)

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

By the Bioenergy Carbon Capture and Storage (BECCS) Task Force

APRIL 4, 2018

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This report was prepared for the CSLF Technical Group by the participants in the Bioenergy with Carbon Capture and Storage Task Force: Mark Ackiewicz and John Litynski (United States, Chair); Jasmin Kemper from the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG); Roman Berenblyum from the International Research Institute of Stavanger (IRIS) in Norway; Noah Deich from the Center for Carbon Removal; and external reviewers from IRIS, CO2GeoNet, the Center for Carbon Removal, the Research Council of Norway, Sintef, and Shell.

Each individual and their respective country has provided the necessary resources to enable the development of this work.

The task force members would like to thank Christopher Babel of Leonardo Technologies, Inc. (United States), for coordinating, editing and managing the information contained in the report.

This report represents a review of the current status and potential for Bioenergy with Carbon Capture and Storage and does not necessarily represent the views of individual contributors or their respective employers.

EXECUTIVE SUMMARY

At the Carbon Sequestration Leadership Forum (CSLF) Meeting held in London, United Kingdom in June 2016, the CSLF Technical Group formally moved forward with a task force to identify commercial status, technology options and pathways, resource assessments and emission profiles, as well as an economic analysis for Bioenergy Carbon Capture and Storage (BECCS). This effort supplements carbon capture and storage (CCS) technologies that have been the main focus of CSLF efforts since its inception in 2003.

The term BECCS refers to the concept of combining bioenergy applications (including all forms of power, heat, and fuel production) with CCS. BECCS projects have the potential to be negative emissions technologies (NETs) that can remove CO_2 emissions from the atmosphere by either stimulating natural carbon uptake and increasing terrestrial and aquatic carbon sinks or applying engineering approaches. One of the strengths of BECCS is that it can be applied to a wide range of technologies with varying amounts of CO_2 emissions, e.g., dedicated or co-firing of biomass in power plants, combined heat and power plants (CHPs), pulp and paper mills, lime kilns, ethanol plants, biogas refineries, and biomass gasification plants.

BECCS has the technical potential to mitigate up to 3.3 GtC per year. However, deployment of BECCS at the technical potential as a major climate mitigation solution will necessitate planting bioenergy crops on approximately 430-580 million hectares of land. This is approximately one-third of the arable land on the planet or about half of the U.S. land area. Clearing this amount of land for bioenergy crops will be associated with its own direct and indirect emissions as a result of: (1) land cover change, (2) loss of forests and native grasslands, (3) soil disturbance, and (4) increased use of fertilizer. Although the direct CO_2 emissions from biogenic feedstock conversion broadly correspond to the amount of atmospheric CO_2 sequestered through the growth cycle of bioenergy production, the extent of negative emissions will ultimately depend on the total life cycle emissions, which include emissions from the biomass supply chain, energy penalties, time horizon, etc.

Further areas of uncertainty exist in understanding whether biomass energy can serve as an important tool for mitigating carbon emissions. Research, experimentation, and modeling approaches have the potential to narrow some areas of uncertainty and provide the much-needed data to de-risk technological solutions. For biomass conversion and wide-scale deployment of bioenergy to reduce greenhouse gas (GHG) emissions or achieve negative emissions, the processes must be integrated with carbon capture, utilization and storage (CCUS). Today, there is limited practical and research experience of dedicated BECCS technologies at scales necessary for climate mitigation, but lessons learned from the deployment of CCUS technologies apply to BECCS as well. Currently, the majority of major BECCS projects are located at ethanol fermentation plants. And half of those projects use the CO_2 for enhanced oil recovery (EOR), highlighting the importance of CO_2-EOR as a driver for commercializing BECCS and utilizing EOR as an early economic driver.

Along with the lack of commercial use, there are several barriers to large scale deployment of BECCS technologies. Some of these barriers arise from technical, economical, governmental, perception, land use, resource availability, and other developmental hurdles. To overcome these obstacles, there is an urgent need for not only research and development, but financial mechanisms, incentives, government support, and policies to promote the benefits associated with BECCS.

To advance technical issues, there is a need for establishing research programs exploring BECCS concepts. These research programs should focus on outlining a way to achieve the commercial deployment of BECCS for each industrial application and at various scales. These programs should include:

- Evaluating the impact of CO_2 capture on plant operations and competitiveness: The capture of CO_2 from ethanol plants is less energy intensive than capturing CO_2 from cement or pulp/paper mill flue gases. Systematic evaluation of the impacts on production cost, operational costs is needed for all BECCS approaches.
- Studying the impact of gas stream impurities on CO_2 capture technologies that were developed for the power generation industries: The types and composition of impurities in gas streams from biomass co-firing, ethanol, biomass-to-liquids plants, cement, and waste incineration plants is different from those encountered in gas streams in power plants. For instance, waste incineration plant flue gas may require pretreatment to remove chlorine, dioxins, and other compounds before the CO_2 separation step.
- Exploring novel means to recover waste heat from industrial processes and integrate this with the CO_2 capture and compression step: Part of the steam required for CO_2 capture from paper and pulp and cement gas streams can be recovered from flue gas waste heat. Studies on the heat/process integration between the CO_2 capture process and the production plant are needed to gauge what level would be most optimal.
- Exploring the diverse incentives and opportunities that drive the adoption of BECCS: With the exception of pulp and paper, most other processes (co-firing, liquefaction, ethanol, cement, waste to energy) are driven by incentives and regulations such as renewable energy portfolio standards, industry GHG standards, high waste disposal fees, and production and/or investment tax credits. These factors determine the economic feasibility of the capturing and storing of biomass-derived CO_2.

Recommendations developed by the BECCS Task Force include:

- Inform policymakers with respect to the benefits of BECCS market opportunities, opportunities for EOR and negative carbon emissions.
- Develop a common framework for lifecycle assessment to facilitate accurate accounting of BECCS carbon footprint.
- Perform research to develop and identify biomass feedstocks that require limited processing.
- Perform continued research to develop and identify new capture technologies that will have a substantially lower capital and energy cost affecting the cost of electricity.
- Develop regional organizations to track and monitor feedstock availability to insure sufficient quantities can be provided for continuous power generation.
- Incentivising the double benefit of BECCS can help avoid direct investment competition with other abatement options. Concerted efforts, e.g., global forest protection policies, carbon stock

incentives, and bioenergy/renewable energy incentives, are necessary to avoid undesirable land use change (LUC) emissions.

- Early BECCS projects should aim to use mainly "additional" biomass and 2nd generation biofuel crops to avoid adverse impacts on land use and food production. However, additional biomass may be costlier or have other adverse impacts.
- BECCS options that optimize water use and carbon footprint need to be identified through careful selection of crops, location, cultivation methods, pre-treatment processes, and biomass conversion technologies. Sustainable biomass feedstocks will require avoidance of unsustainable harvesting practices, e.g., exceeding natural replenishment rates. Using "additional biomass" to avoid sustainability issues also helps improve public acceptance.
- Sustainability needs to be ensured across the whole BECCS chain. Improving pre-treatment processes for biomass (i.e., densification, dehydration, and pelletisation) will make biomass transport more efficient and remove geographical limitations of biomass supply.
- BECCS project developers and advocates should focus more on building up trust with the general public and local communities, instead of just providing educational information.
- Stronger collaboration and exchange of ideas between stakeholders of the CCUS, bioenergy, and BECCS industries would also be beneficial and are recommended.

Contents

1 Introduction

1.1 CSLF Purpose

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

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

The Technical Group has the mandate to identify key technical, economic, environmental, and other issues related to improving technological capacity and establishing and regularly assessing potential research and technology gaps.

At the CSLF Meeting held in London, United Kingdom in June 2016, the CSLF Technical Group formally moved forward with a task force to identify commercial status, technology options and pathways, resource assessments and emission profiles, as well as an economic analysis for BECCS. This effort supplements CCUS technologies that have been the main focus of CSLF efforts since its inception in 2003.

1.2 Task Force Mandate

The United States proposed to serve as chairperson and lead a Technical Group Task Force that is focused on identifying the commercial status, technology options and pathways, resource assessments and emission profiles, as well as an economic analysis for BECCS. The Task Force will develop a report that will:

- Identify the existing projects, government programs, market drivers for BECCS deployments, barriers to large-scale BECCS demonstration and deployment, and opportunities and recommendations for overcoming barriers progress;
- Provide an overview of BECCS technology options and pathways: (power; fuels and chemicals production; industrial sources; summary of technical challenges and R&D opportunities);
- Summarize resource assessments and emissions profiles: existing reports and analyses; biomass and carbon storage resource assessments; direct and indirect GHG emissions; summary of life cycle assessments; identification of gaps in analyses and future opportunities;
- Summarize economic analyses for BECCS concepts;
- Include findings and recommendations for consideration by CSLF and its member countries.

1.3 Overview of BECCS and Bio-CCS

The terms BECCS and Bio-CCS both refer to the concept of combining bioenergy applications with CCS. CCS describes processes that separate a relatively pure stream of CO_2 from industrial or power plants and store the conditioned and compressed gas in suitable geological formations (IPCC, 2005).

Throughout the published literature, terminology and definition of BECCS and Bio-CCS are not entirely consistent, and both are used alternatively. Definitions of Bio-CCS can be as simple as "*[…] CCS, in which the feedstock is biomass* (IPCC, 2005) or as comprehensive as "*[…] processes in which CO_2 originating from biomass is captured and stored. These can be energy production processes or any other industrial processes with CO_2-rich process streams originating from biomass feedstocks. The CO_2 is separated from these processes with technologies generally associated with CCS for fossil fuels. Biomass binds carbon from the atmosphere as it grows; but with the conversion of the biomass, this carbon is again released as CO_2. If, instead, it is captured, transported to a storage site and permanently stored deep underground, this would result in a net removal of CO_2 from the atmosphere*" (ZEP and EMTP, 2012). Figure 1 shows the general concept of coupling bioenergy with CCS.

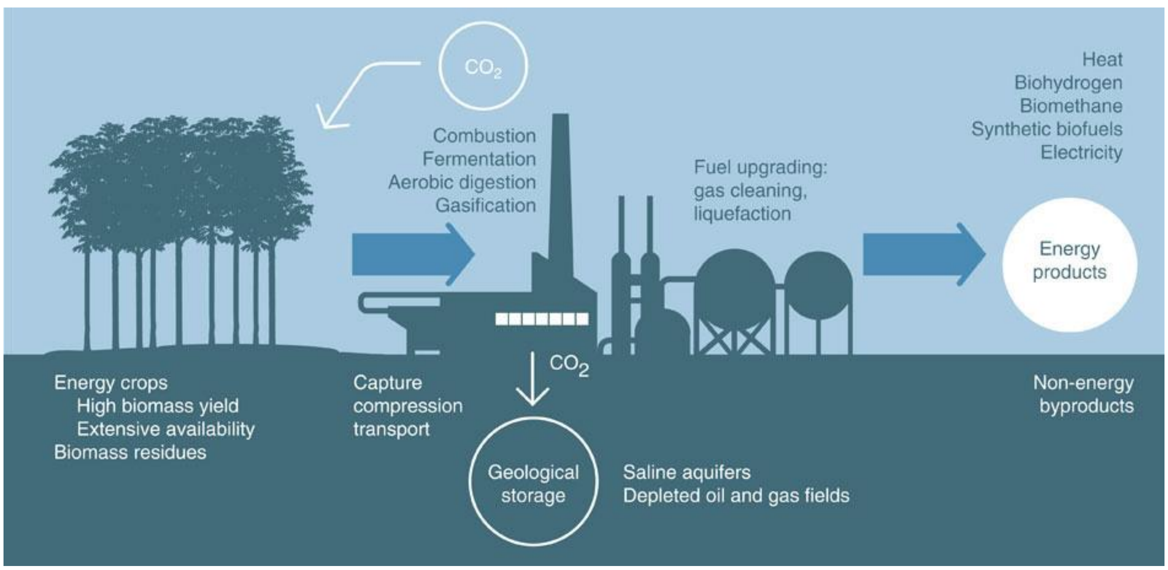

Figure 1: Concept of Bio-CCS (Canadell & Schulze, 2014)

Although some references use BECCS in the broad sense as an application of CCUS to bioenergy conversion processes (IPCC, 2014), some use it to refer to the process of biomass combustion for energy with subsequent CCUS only, especially in the power sector. Bio-CCS, on the other hand, appears generally in a wider context of sequestration, i.e., includes using the captured biogenic CO_2 as a feedstock to produce algae, plastics, transport fuels, animal feed, or other materials/chemicals (Gough & Upham, 2010). Thus, Bio-CCS usually has a broader definition that includes BECCS technologies if these are defined to cover only biomass combustion processes. This report will be using the term BECCS, assuming it includes all forms of power, heat, and fuel production.

BECCS projects have the potential to be negative emissions technologies (NETs) that can remove CO_2 emissions from the atmosphere by either stimulating natural carbon uptake and increasing terrestrial and aquatic carbon sinks or applying engineering approaches. The portfolio of proposed NETs often includes land and ocean-based CO_2 mineral sequestration (mineral carbonation), large-scale afforestation, soil carbon sequestration, direct air capture and storage (DACS), BECCS, and the more speculative approach of iron fertilization of the oceans to promote biomass growth (Williamson, 2016). As a NET, BECCS can lead to a net removal of CO_2 from the atmosphere (IEA, 2011; IEAGHG, 2011). Like the terms BECCS and Bio-CCS, the definition of NETs is not clear at times due to partially overlapping definitions, e.g., with mitigation. Although the direct CO_2 emissions from biogenic feedstock conversion broadly correspond to the amount of atmospheric CO_2 sequestered through the growth cycle of bioenergy production, the extent of negative emissions will ultimately depend on the total life cycle emissions, which include emissions from the biomass supply chain, energy penalties, time horizon, etc.

1.4 Challenges and Benefits of BECCS

BECCS is one of the few technologies that have the potential to enable the world to limit warming to 2°C or below by 2100 (Azar, Lindgren, Larson, & Möllersten, 2006; van Vliet, den Elzen, & van Vuuren, 2009; Krey, Luderer, Clarke, & Kriegler, 2014; Kriegler, et al., 2014; IPCC, 2014; Tavoni & Socolow, 2013). One of the strengths of BECCS is that it can be applied to a wide range of technologies with varying amounts of CO_2 emissions, e.g., dedicated or co-firing of biomass in power plants, combined heat and power plants (CHPs), pulp and paper mills, lime kilns, ethanol plants, biogas refineries and biomass gasification plants (Karlsson & Byström, 2011). BECCS also provides a technology pathway for countries to surpass the target emission reduction values in the near-term within the mitigation scenarios (IPCC, 2014). In addition, BECCS can provide a buffer to tackle emissions in sectors where reductions are harder to achieve due to economic, political, or technical constraints (e.g., aviation, shipping, iron and steel making, etc.).

As a technological solution, deploying BECCS will be essential to address broader issues related to both CCUS and bioenergy. Several studies have already addressed the technical and economic challenges of CCUS technologies (e.g. Gibbins & Chalmers, 2008; Pires, Martins, Alvim-Ferraz, & Simoes, 2011; Nykvist, 2013; Boot-Handford, et al., 2014; Leung, Caramanna, & Maroto-Valer, 2014). When considering the application of BECCS in bioenergy, sustainability at scale and engineering challenges for large-scale biomass conversion remain knowledge and R&D gaps.

2 Summary of Resource Assessments and Emissions Profiles

2.1 Biomass and Carbon Storage Resource Assessments

2.1.1 Biomass

Biomass is any organic matter that can be renewable and available as a feedstock for bioenergy, which can come from agricultural crops, forestry products, municipal and other waste (WBDG, 2016), and microalgae and bacteria. Primary bioenergy uses farmland or forests to produce biomass and the other biomass can come from residue generated as a by-product of food or wood production throughout the supply-consumption chain (IRENA, 2014). Biomass accounts for 10% of global primary energy used for heat and electricity (IEA, 2017) and is also utilized for industrial processes (for example, the production of chemicals and pharmaceutical products) and to make transportation fuels. The United States leads the world in biomass-generated electricity, followed by Germany, China, and Brazil (NEB, 2017). Biomass resource assessment includes the technically available, economically recoverable, and sustainable potential for biomass resources and their projected change over time. Today, an upper estimated 1.2 billion hectares (ha) of surplus land is available for bioenergy crop production (FAO, 2014; IRENA, 2014), approximated by subtracting land demand for non-energy uses from potentially available, but without considering sustainability or economic feasibility factors. Estimates of bioenergy land availability are sensitive to key variables, such as agricultural productivity and demand and population growth. Low estimates (approximately 1/3 of the current energy supply) of global biomass supply to drive bioenergy deployment assume that there is limited land available for bioenergy crops and the limitation are driven by high demand for food, but little expansion of agriculture into forested landscapes and limits to productivity increases (Lewis & Kelly, 2014). Midrange estimates (approximately half of the current global primary energy supply) assume that agricultural productivity can keep pace with population growth and high estimates (more than current global primary energy supply) assume that agricultural yields outpace demand for food and that land mass the size of China becomes available for bioenergy crop production (Slade, Saunders, Gross, & Bauen, 2011).

Sustainability indicators for biomass energy vary, but the Global Bioenergy Partnership (GBEP) inter-governmental initiative of 50 national governments and 26 international organizations was established to implement uniform sustainability indicators and, as of 2015, has been implemented in six countries. The goal of GBEP is to support national and regional bioenergy policy-making and market development within a sustainability framework and facilitate bioenergy integration into energy markets by addressing the market barriers within countries and across regions. These goals rely on robust methodologies to address the policy and market impacts of deploying bioenergy widely and include life cycle assessments for GHG emissions from bioenergy production. Life cycle assessments address which GHGs are included, the sources of biomass, land use changes due to bioenergy production, biomass feedstock production, transport of biomass, processing into fuel, by-products and co-products, transport of fuel, fuel use, and comparison of the GHG associated with those steps with replaced fuels.

Along with GHG assessments, bioenergy sustainability also includes impacts on soil quality, biomass quality, harvest levels, water use and efficiency, water quality, and impacts on biological diversity in the landscape where bioenergy production is proposed. There are also social impacts to consider, including allocation of land for bioenergy crops, the impacts on the price and supply of other commodities (with larger impacts in developing nations), jobs in the bioenergy sector, and associated changes in the work force. Bioenergy crops and agricultural resources are often produced using the same land resources and as bioenergy demand increases, competition for land and market dynamics are expected to put those sectors at odds with each other. In countries with insufficient resource bases to cover both demands for bioenergy and food production, food production is expected to be prioritized (IRENA 2014). The benefits of shifting to bioenergy in developing countries include adding value to traditional use of biomass for energy, diversifying the energy landscape, building capacity and flexibility, and training the workforce (GBEP, 2011).

2.1.2 Carbon Dioxide Utilization and Storage

For biomass conversion and wide-scale deployment of bioenergy to reduce GHG emissions or achieve negative emissions, the processes must be integrated with CCUS (IEAGHG, 2014). Carbon sequestration can be used to describe both natural and technology-driven processes to remove CO_2 from the atmosphere or divert CO_2 emissions to long-term storage sites in the ocean, in soils or sediments, or in geologic formations. Because the natural CO_2 uptake mechanisms are insufficient to offset the pace of emissions from human activities, there is a need to enhance natural and deliberate uptake mechanisms and utilize long-term CO_2 storage. To reach the less than 2°C goal set forth by the Intergovernmental Panel on Climate Change (IPCC) and agreed upon at COP21, global annual CO_2 emissions must be reduced from the current level of ~54 Gt CO_2-eq/year to approximately 42 Gt CO_2-eq/year by 2030 and 22 Gt CO_2-eq/year by 2050 (Rogelj et al., 2016), while global population and energy use continue to grow. Carbon removal and storage will be a critical component for achieving these ambitious carbon emission reduction targets.

Terrestrial carbon sequestration includes afforestation, wildfire and disease outbreak suppression, soil conservation, and enhanced weathering. The world's forests present one potential carbon sink estimated to be 2.4GtC/year (Pan, et al., 2011; Ni, Eskeland, Giske, & Hansen, 2016) which would require a combination of planting and replanting programs and drastically reducing global deforestation rates. The wood (biomass is 50% carbon) can be collected and combusted with CCUS (BECCS) or stored in bulk storage facilities or utilized in long-lasting applications (Scholz & Hasse, 2008). The scale of potential in carbon storage varies geographically (Kraxner, Nilsson, & Obersteiner, 2003), but tropical regions have the highest potential for storing carbon in forests (Ni, Eskeland, Giske, & Hansen, 2016) and though boreal peatlands hold vast amounts of carbon, they are rapidly warming, accelerating the release of that stored carbon back into the atmosphere. Thus, land management practices and the potential to disrupt other present-day activities like agriculture and urban development play critical roles in the capacity of terrestrial carbon sequestration to offset carbon emissions.

Oceanic natural carbon uptake is currently net 2 GtC/year (Solomon, et al., 2007) but the potential to enhance natural uptake in the oceans is limited because the oceans become more acidic as more CO_2 reacts with sea water, with negative effects on marine organisms that form carbonate skeletons and shells (Orr, et al., 2005, Hofmann et al., 2010). Overcoming the issues of ocean acidification is possible but would require increasing alkalinity to enhance ocean-based mineral carbonation. Though technically feasible using a variety of engineering approaches, the potential cost and unintended consequences cannot be ignored (Ravel, et al., 2005).

Geologic carbon sequestration holds the potential to store vast amounts of CO_2. When CO_2 is captured from a point source, such as a power plant or industrial facility, it is piped and injected 1-4km below the land surface into porous rock formations, where it can remain for millions of years. The capacity for geologic storage varies geographically and is constrained by the volume and distribution of storage sites. For example, CO_2 can be stored in depleted oil and gas reservoirs, unmineable coal beds, and saline aquifers. In the U.S. alone, between 900-3400 GtC can be stored in deep geologic reservoirs (NETL, 2015), orders of magnitude more storage than could be produced from burning our fossil energy resources.

2.2 Direct GHG emissions

Greenhouse gases (GHGs) include CO_2, CH_4, N_2O, and halocarbons (organic compounds that contain chlorine, bromine, or fluorine) – these gases are emitted from human activities directly or indirectly (IPCC, 2007). Direct emissions are emissions that can be attributed to a point source in a sector, technology, or activity (for example, emissions from a coal-fired power plant). Indirect emissions are attributed to an end-use sector (for example, emissions from growing bioenergy crops for BECCS).

In December 2016, the average CO_2 concentration in the atmosphere was 404.48 ppm, a dramatic increase relative to the pre-industrial level of 280ppm (ESRL, 2017). The energy sector contributed 68% of the global anthropogenic GHGs and fossil energy resources accounted for 82% of the global total primary energy supply in 2014. CO_2 emissions from energy supply came from two sectors: electricity and heat generation. Transportation and industry accounted for an additional 42% of CO_2 emissions in 2014 (IPCC). The six largest emitting countries/regions in 2015 were China (29%), the United States (14%), the EU (10%), India (7%), the Russian Federation (5%), and Japan (3.5%) (ESRL, 2017).

Global GHG emissions in 2010 were estimated to be 48 Gt CO_2-eq/year and are expected to reach approximately 65 Gt CO_2-eq/year if no climate policies are enacted (Rogelj, et al., 2016). Reaching global emissions targets set forth during COP21 will require bringing annual global emissions below 20 Gt CO_2-eq/year and mitigating upwards of 600 Gt of CO_2 over the 20th century. This level of emission reductions may necessitate wide deployment of NETs like BECCS, which can be applied to reduce emissions from electricity and heat generation as well as some industrial processes, largely those where combustion of fossil fuels such as coal and natural gas can be replaced with biomass and CO_2 can be captured at the stack.

BECCS has the potential to mitigate up to 3.3 GtC per year (Smith, et al., 2016). However, deployment of BECCS as a climate mitigation solution will necessitate planting bioenergy crops on approximately 430-580 million hectares of land (approximately one-third of the arable land on the planet or about half of the U.S. land area (Williamson, 2016)). Clearing this amount of land for bioenergy crops will be associated with its own direct and indirect emissions as a result of (1) land cover change, (2) loss of forests and native grasslands, (3) soil disturbance, and (4) increased use of fertilizer. When these emissions are considered, BECCS is estimated to be able to remove 391 Gt of CO_2 by the end of the century (IPCC RCP2.6 scenario) if bioenergy crops are planted on abandoned land only (Williamson, 2016). But if large forested areas are converted to bioenergy croplands, the result will be a net release of 135 Gt of CO_2 by 2100 (Williamson, 2016). If BECCS is deployed alongside with other NETs or if alternative feedstocks (such as ocean biofuels and algae) are utilized in place of bioenergy crops, the impacts associated with land use may be much lower, although the effects of wide scale harvesting of these resources is uncertain at this point (IEAGHG, 2011).

Over and above uncertainty about the size and direction of emission reductions associated with BECCS, there are gaps in our understanding of how bioenergy crops will respond to future climate conditions, including the increased climate variability, coupled with increased water scarcity. Droughts, fires, and pests are all expected to become bigger problems in the 2nd half of the 20th century (IPCC, 2014) and these will directly and indirectly impact bioenergy crops.

2.3 Indirect GHG emissions

Indirect emissions are attributed to an end-use sector (for example, emissions from the generation of purchased electricity, heat or steam, production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, among others).

Indirect emissions associated with BECCS can come from land use change, soil disturbance, and emissions from processes associated with growing bioenergy crops and these indirect emissions can be estimated using Life Cycle Assessments (LCAs, next section). Despite their wide use, LCA results can vary substantially based on the sources of data, the scope of the analyses, and the required assumptions. LCA analyses often lack real-world data because there are so few projects in operation today. Within the LCA analysis framework, bioenergy crops and fuels should be evaluated based on their specific carbon emissions criteria, both direct and indirect. This context of accounting for both direct and indirect emissions is necessary to label a particular technology or process as carbon neutral or negative and may be the simplest and most transparent means of setting standards for sustainability and responsible production.

2.4 Summary of Life Cycle Assessments

<u>Life Cycle Assessment Methods:</u>

Life cycle assessment methods (LCAs) have been developed to complete a mass balance and to identify and evaluate risks of unintended consequences such as leakage. LCAs may be attributional (dominated by process chain analysis) - seeking to establish burdens associated with the existing production and use of a product, or with a specific service or process at a point in time. LCAs may also be consequential (utilizing input/output methods) - seeking to identify the consequences of a pending decision or a proposed change in a system. All assessments, regardless of scope, face data constraints.

In general, CCUS technologies, including BECCS, have the potential to reduce life cycle emissions (Singh, et al., 2012, Schakel, et al., 2014). Life cycle emissions of BECCS can vary depending on type of biomass feedstock, geographic region covered in the study, time frame, scale, and biomass production methods. The scope of the analysis can include construction, resource extraction or production, operation, post-project dismantling, upstream and downstream waste disposal for all components and capture-specific upstream and downstream processes, fuel (for combustion processes), and resultant GHG emissions. The definition of the boundaries in life cycle emission analyses strongly influence the final reported emissions. For LCAs to be useful, boundaries must be clear and justifiable.

Biomass feedstock options with low life cycle emissions have already been identified and include, e.g., sugarcane, miscanthus, short rotation coppices (SRC), fast-growing tree residues (residues can include agricultural and wood residues) and wastes (biogenic wastes that are not cultivated, including manure, organic waste, and sludge) (Clarke, et al., 2014, Smith, et al., 2014). Emissions reductions are also possible for options that have been perceived as less sustainable in the past, like corn ethanol. Measures include improvement in ethanol production technologies, increase in corn yields and advances in corn production methods. Innovations in the farming sector can directly result in a decrease in indirect land use change (iLUC) and related emissions (Flugge, et al., 2017). The majority of emissions can also come from land use change (LUC) and fossil fuel use for biomass production and pre-treatment (IPCC, 2014), so these areas provide ample opportunity for improvement.

Key areas of uncertainty in both attributional and consequential analyses include dealing with indirect versus direct emissions and their impacts on policies, regulations, and carbon crediting systems. Some analyses seek to allow these measures to be flexible – ostensibly to identify optimal strategies - while others treat them as fixed and report on the consequences. The following subsections will provide examples of recent approaches to deal with indirect versus direct emissions and highlight the confusion that can arise when the treatment of these two key uncertainties is not explicit.

The International Organization for Standardization (ISO) has published a series of consensus standards that are focused on principles and practices for LCAs.[1] ISO standards are presented as guidelines and collections of best practices and refer to four components (BSI, 2011; WRI, 2011):[2]

- Goal definition and scoping: Define and describe the product, process, or activity being studied. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.
- Inventory analysis: Identify and quantify energy, water, and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
- Impact assessment: Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
- Interpretation: Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process, or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

These four ISO components are not highly restrictive, and boundaries can be drawn narrowly to focus the analysis close to an individual location or broadly, as is often the case for GHG mitigation analyses.

LCA analyses often suffer from uncertainties associated with incomplete data or knowledge of inputs and outputs (IEAGHG, 2014). When used properly and described clearly, LCAs can provide valuable data for use in Integrated Assessment Models. However, many aspects of LCA practice and methodology are overlooked or misunderstood (Curran, 2013). These include:

- Goal setting and definition of the functional unit;
- Allocating environmental burdens across co-products from a process;
- Giving credit for avoided burden;

[1] Principles and procedures that can be applied to perform life cycle assessments (LCA) are part of the ISO 14000 environmental management standards: in ISO 14040:2006 and 14044:2006. Additional standards are available which clarify the procedures or that serve as examples for specific industries.

[2] International Standards Organization. 1997: Environmental Management - Life Cycle Assessment - Principles and Framework ISO 14040; International Standards Organization. 1998. Life Cycle Assessment - Impact Assessment ISO 14042; and International Standards Organization. 1998b. Environmental Management - Life Cycle Assessment - Life Cycle Interpretation ISO 14043.

- Understanding the difference between attributional and consequential LCAs;
- Availability of inventory data and transparency of that data;
- Assessing data uncertainty;
- Differentiating life cycle risk assessment and other risk assessment;
- Reporting qualitative as well as quantitative data (but identifying each as what it is);
- Acknowledging that LCA may not define the "best" option; and,
- Recognizing LCAs are iterative in nature and may be better used as a comparative tool.

Studies assessing the life cycle emissions:

LCA results can indicate the amount of CO_2 that is avoided using biomass and the additional reduction that arises when the emitted CO_2 is captured. They can also show that not all sources of biomass yield similar GHG benefits when CCUS is added. A paper by Muench (2015) compares the mitigation potential for various biomass fuels by species and purpose (waste versus dedicated crop) when these are utilized for power and for transportation. The comparative results are shown in Figure 2 below.

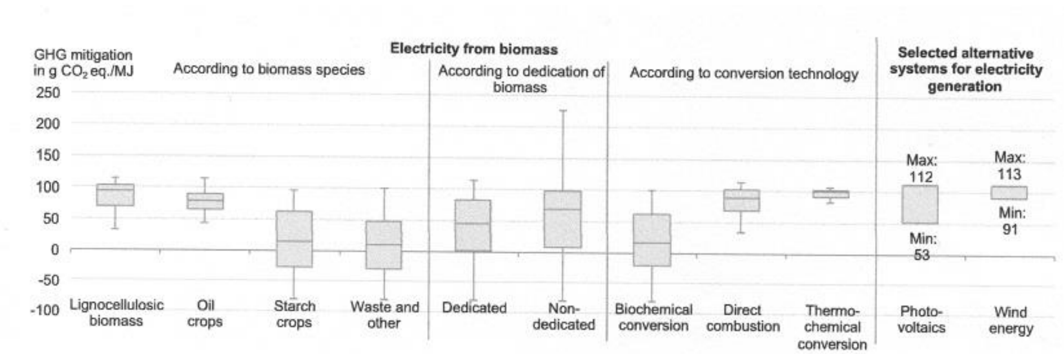

Figure 2: Global Warming Mitigation Potential of Biomass Electricity (Muench, 2015)

Not all sources of biomass or conversion technology are carbon neutral. Similarly, adding CCUS will result in different overall negative emissions.

Comparing various combustion options, including co-firing and dedicated biomass combustion, the net life cycle CO_2 emissions appear to depend on biomass type and the combustion method (Weisser, 2007; Odeh & Cockrell, 2007; Cai, et al., 2014; Schakel, et al., 2014). The net life cycle CO_2 emissions also depend on the data, LCA methodology, and analysis assumptions, and in many cases, the data and assumptions are inaccurate or out of date (Schakel, et al., 2014).

Table 1: Life-cycle CO_2 emissions comparing combustion technology and biomass content (See Schakel, Meerman, Talaei, Ramirezrez, & Faaij, 2014 for Study references)

Study (citation number)	Technology	Biomass Type	Co-firing Ratio (%)	Capacity (MW)	Life-cycle CO_2 emissions (g/kWh)	Net Life-cycle CO_2 emissions (g/kWh)
Spath and Mann (1)	Co-firing	Urban waste – energy crops	15	600	270	43
Corti & Lombardi (2)	BIGCC[a]	Poplar	100	205	70-130	-410
Carpentieri et al. (3)	BIGCC[a]	Poplar	100	191	227	-594
NETL (4)	IGCC[b]	Switch grass	30 (weight)	451-654	Not reported	-6 to -105
NETL (5)	Super-critical coal co-firing plant	Hybrid poplar	30	550	Not reported	38
Cuellar (6)	Coal co-firing plant	Forest residues	20	141.5	Not reported	-129.5
Schakel (7)	PC[c]	Wood pellets/straw pellets (residue)	30	550	281-291	-67 to -72
Schakel (7)	IGCC[b]	Wood pellets/straw pellets (residue)	30	550	253-262	-81 to -85
(a) Biomass gasification combined cycle; (b) Integrated gasification combined cycle; (c) pulverized coal-fired						

2.5 Identify Gaps in Analyses and Future Opportunities

Key areas of uncertainty exist in understanding whether biomass energy can serve as an important tool for mitigating carbon emissions. Research, experimentation, and modeling approaches have the potential to narrow some areas of uncertainty and provide the much-needed data to de-risk technological solutions. When considering the potential for bioenergy from forestry, global land cover datasets provide an important starting point - differences in estimates of land cover among global datasets can be upwards of 35% (Thomson, et al., 2010), a key piece of uncertainty that limits the ability to accurately model BECCS potential globally. Planting trees for energy generation or carbon sequestration must not endanger food security (DeFries and Rosenzweig, 2010; Smith, et al., 2013) and put further restrains on the potential for afforestation and bioenergy. Many least costly options for enhancing carbon sequestration in forestry projects are in Africa, South America, and Asia; but these are contingent upon risk profiles and within-country volatility (Benitez & Obersteiner, 2006). Although afforestation can cost less than deployment of BECCS technologies, both afforestation and BECCS options offer promise for effective mitigation options (Humpenöder, et al., 2014). The relative merits of each vary with policy choices and the length of time that these CO_2 mitigation approaches are pursued. The standalone and combined mitigation potential of afforestation and BECCS depends on trade-offs like competition for land or path dependencies constrained by earth system responses and cumulative emission budgets, bioenergy potential, CCUS capability, and significant political and socio-economic factors. Variations in the potential of biomass energy to mitigate carbon emissions rely on land area availability relative to food production along with forestry practices, and thus constitute a key uncertainty, especially when combined with changing water resources, direct and indirect land use change, biodiversity, social acceptability and policy frameworks (Azar, et al., 2010; Bonsch, et al., 2014; van Vuuren and Riahi, 2011). Today, CCUS technology is in the demonstration phase and uncertainty is diminishing. There is limited practical and research experience of dedicated BECCS technologies, but lessons learned from the deployment of CCUS technologies apply to BECCS as well.

A transparent and readily understood system to account for carbon emissions can assist in the deployment of BECCS technologies. It may also help define what kinds of fuels are preferable if the goal is carbon emission reductions and could be demonstrated as carbon saved or removed and/or produced.

Although carbon accounting of the combination of CCUS with bioenergy is possible, there are some uncertainties in ensuring the process delivers genuine net 'negative' emissions. When biomass is used to generate electricity, GHG reductions vary depending upon the type of biomass used and not all scenarios lead to GHG reductions (Muench, 2015). Addition of CCUS to biomass energy systems should result in net GHG reductions in all cases, but the relative value of the combined technologies can vary. For BECCS to be a useful mitigation technology, global participation and widespread deployment would be required to significantly impact projected atmospheric concentrations of carbon dioxide later in this century (Tilman, et al., 2009).

3 Commercial Status of BECCS Technology Deployment

3.1 Planned and Existing Projects

A complete list of BECCS projects can easily turn out to be a very comprehensive one, as the technology is suitable in a variety of facilities from different sectors, e.g., power, heat, industrial. In addition, there is a potential overlap with coal-CCUS and gas-CCUS projects if a project would decide to switch all or part of their fuel supply to biomass. Table 2 provides a list of existing, planned, completed and cancelled projects where information was available. The table shows select key characteristics, such as status, CO_2 capacity, source, and sink.

There are currently five BECCS projects in operation, which capture approximately 1.85 $MtCO_2$/yr (see Table 2). The Norwegian Government has set a goal to construct at least one full-scale carbon capture demonstration plant by 2020. The Ministry of Petroleum and Energy has supported three feasibility studies in 2016, of which two are BECCS: The Klemetsrud Waste-to-Energy Plant and the NORCEM cement plant. Based on the result from the studies, Gassnova recommends that all three should continue preparing for the front end engineering design (FEED) phase (GASSNOVA, 2016).

In the United States, the Illinois Industrial CCS Project (IL-ICCS) is capturing 1 $MtCO_2$/yr. It became operational in April 2017 and is now the largest operating BECCS project. This is an important milestone for CCUS and will put this BECCS project on par with other large-scale projects, including Boundary Dam with 1 $MtCO_2$/yr, Petra Nova with 1.4 $MtCO_2$/yr, and many industrial gas processing facilities providing 1 $MtCO_2$/yr (including Quest, Lost Cabin, Whiting Petroleum, etc.). The majority of major BECCS projects are located at ethanol fermentation plants. CO_2 capture from ethanol production is a commercially tested and proven technology. The application of BECCS to ethanol plants in Table 2 is dominant because the fermentation process supplies a stream of relative pure CO_2, making its capture relatively simple, only requiring dehydration and compression of the product stream. Half of the projects use the CO_2 for EOR, highlighting the importance of CO_2-EOR as a driver for commercializing BECCS and utilizing EOR as an early economic driver. The U.S. IL-ICCS project is injecting its CO_2 into the Mount Simon saline bearing sandstone over a mile below the facility and is planning to claim 45Q tax credits from the U.S. government, highlighting the importance of government incentives for early adoption of the technology. Furthermore, planned projects are clustered in certain regions, e.g., North America, Japan, Scandinavia, and other specific European locations. Though the number of BECCS projects that are either operational or underway is encouraging, significantly more CCUS projects will be necessary to achieve the required CO_2 emission reductions and to build up operational knowledge and confidence in the technology at large/commercial scale.

Table 2: Summary of global BECCS projects (Kemper 2015)

Project name	Location	Status	CO_2 capacity $MtCO_2$/yr	CO_2 source	CO_2 sink
Operational projects					
IL-ICCS project	Decatur, IL, USA	2nd phase operating since April 2017	1.0	Archer Daniels Midland ethanol plant, other	Saline storage, Mount Simon sandstone
Arkalon	Liberal, KS, USA	Operating since 2009	0.18-0.29	Conestoga's Arkalon ethanol plant	EOR, Booker and Farnsworth oil fields, TX
Bonanza	Garden City, KS, USA	Operating since 2011	0.10-0.15	Conestoga's Bonanza BioEnergy ethanol plant	EOR, Stuart oil field, KS
RCI/OCAP/ROAD	Rotterdam, NL	Operating since 2011	0.1 (Abengoa) 0.3 (Shell)	Shell's Pernis refinery, Abengoa's ethanol plant, Maasvlakte power plant, various other	Nearby greenhouses, TAQA's P18-4 gas reservoir after 2015
Husky Energy	Lloydminster, SK, CA	Operating since 2012	0.09-0.1	Ethanol plant	EOR, Lashburn and Tangleflags oil fields
Planned projects / projects under evaluation					
Klemetsrud	Oslo, NO	Planned start in 2022	0.3	Waste-to-energy plant, 50-60% biomass	Smeaheia, North Sea
Norcem	Brevik, NO	Planned start in 2022	0.4	Cement plant, >30% biomass	Smeaheia, North Sea
Mikawa power plant	Omuta, Fukuoka, JP	Planned start in 2020, pilot-scale CO_2 capture since 2009	0.18	Mikawa power plant (coal and/or biomass)	Not yet identified
C.GEN North Killingholme Power Project	North Killingholme, UK	Evaluating, planned start in 2019, now likely cancelled	2.5	Biomass co-fired IGCC power plant	Southern North Sea
Södra	Värö, SE	Identifying and evaluating	0.8	Pulp and paper mill	Skagerrak, North Sea
Domsjö Fabriker	Domsjö, SE	Identifying and evaluating	0.26	Black liquor gasification pulp mill	Saline aquifer, North or Baltic Sea
Lantmännen Agroetanol	Norrköping, SE	Identifying and evaluating	0.17	Ethanol plant	Saline aquifer, North Sea
CPER Artenay project	Artenay and Toury, FR	Identifying and evaluating	0.045-0.2	Tereos ethanol plant	Dogger and Keuper saline aquifers, Paris Basin,
Sao Paulo	Sao Paulo state, BR	Identifying and evaluating	0.02	Ethanol plant	Saline aquifer
Biorecro/EERC	ND, USA	Identifying and evaluating	0.001-0.005	Gasification plant	Saline aquifer
Skåne	Skåne, SE	Identifying and evaluating	0.0005-0.005	Biogas plant	Saline aquifer
Completed projects					
Russel EOR research project	Russel, KS, USA	Completed 2005	0.004 (0.007 in total)	Ethanol plant	EOR, Hall-Gurny-Field
Norcem	Brevik, NO	Testing 2014-2016, CO_2 capture only	Small-scale	Cement plant, >30% biomass-fueled	N/A
IBDP	Decatur, IL, USA	First phase completed in 2014, now monitoring	0.3 (1.0 in total)	Archer Daniels Midland ethanol plant	Mount Simon sandstone
Cancelled projects					
White Rose CCS Project	Selby, UK	Cancelled	2.0	Drax power station, biomass (co)-firing	Bunter sandstone
Rufiji cluster	TZ	Cancelled	5.0-7.0	Sekab's ethanol plants	Saline aquifer
Greenville	Greenville, OH, USA	Cancelled in 2009	1.0	Ethanol plant	Saline aquifer, Mount Simon sandstone
Wallula	Wallula, WA, USA	Cancelled	0.75	Boise Inc's pulp mill	Saline aquifer
CO_2 Sink	Ketzin, DE	Cancelled	0.08		Saline aquifer

3.2 Projects in Operation

3.2.1 Illinois Basin Decatur Project / Illinois Industrial CCS project

The most relevant BECCS project is the Illinois Basin Decatur Project (IBDP). The world's first large-scale BECCS project has been operational since November 2011. The U.S. Department of Energy (USDOE) funds the project under their Regional Carbon Sequestration Partnership programme (RCSP). The CO_2 in this project comes from the Archer Daniels Midland (ADM) ethanol plant in Decatur, Illinois, with a production capacity of around 350 million gallons per year. The ethanol fermentation process produces a high CO_2 concentration, high water content but low-pressure exhaust gas. This gas is then compressed, dehydrated to around 200 ppm (H_20) and transported 1.6 km by pipeline for injection into a deep saline formation, the Mount Simon sandstone. The Midwest Geological Sequestration Consortium (MGSC), one of the seven regional partnerships under the RCSP, extensively monitors the subsurface injection aspects of the project. The project reached its primary goal of injecting a total of 1 $MtCO_2$ (i.e. 0.33 $MtCO_2$/yr) underground in November 2014 and continues with a 3-year post-closure monitoring programme (Finley, 2014; Jones & McKaskle, 2014).

The Illinois Industrial CCS (IL-ICCS) project now succeeds the IBDP, again with USDOE support. The project expands the CO_2 storage capability to that of a commercial-scale operation, i.e., 1 $MtCO_2$/yr. ADM has integrated the IBDP compression and dehydration facilities with the new facilities constructed under the IL-ICCS project upon completion of IBDP injection operations in autumn 2014 (GCCSI, 2017; NETL, 2015). The main aim is to inject 1 $MtCO_2$/yr (Gollakota & McDonald, 2012) and the project became operational in April 2017.

3.2.2 Rotterdam Climate Initiative

Since 2011, the Organic Carbon Dioxide for Assimilation of Plants (OCAP) project in Rotterdam, Netherlands, has been delivering nearly 0.1 Mt/yr of biogenic CO_2 from the Abengoa ethanol plant and 0.3 Mt/yr of fossil CO_2 from Shell's Pernis refinery to greenhouses nearby, which use the CO_2 as fertiliser (RCI, 2011; Mastop, de Best-Waldhober, Hendriks, & Ramirez, 2014). As it effectively does not store the CO_2, the project is not strictly bio-CCS but rather bio-CCU (biomass with carbon dioxide capture and utilisation). The OCAP project is part of the bigger efforts of the Rotterdam Climate Initiative (RCI), which is planning to develop a CCUS hub, connecting additional CO_2 suppliers to reach demonstration stage capacities. The CO_2 in the Rotterdam hub will include a mixture of biogenic and fossil sources related to the power and industry sector and will involve utilisation as well as storage of CO_2.

Abengoa, an international bioethanol producer, has an ethanol production capacity of approximately 480 million litres per year in the Port of Rotterdam, equivalent to more than 2% of the road transport fuel demand in 2010 of 418 PJ (Mastop, de Best-Waldhober, Hendriks, & Ramirez, 2014). Abengoa is currently working on other projects in the U.S. and France that involve utilization of captured CO_2 for beverage carbonation and refrigeration applications. However, no detailed information about the status of those bio-CCU, or other bio-CCS, activities is available at present.

3.2.3 Norcem

This project investigates CO_2 capture from a cement plant operated by Norcem in Brevik, Norway. Gassnova is funding the project through the CLIMIT programme. The plant's year of construction dates back to 1919, but after refurbishment, it can handle alternative fuels, such as coal mixtures and biomass shares of more than 30%. The flue gas contains approximately 20% CO_2, with fluctuating levels of SO_2. The project involves testing of mature as well as early stage CO_2 capture technologies, such as amines, solid sorbents, membranes, and regenerative calcium cycles. It is a key objective to obtain information about the performance of the different processes when adapted from power plant to cement plant application. The project focuses on the capture step, so will not include any assessment of transport and storage for now. Norcem carried out first estimations showing that conventional amine systems with waste heat utilisation could capture around 30 – 40% of the CO_2 at the Brevik plant, which corresponds to 0.3 – 0.4 $MtCO_2$/yr (Bjerge & Brevik, 2014; GCCSI, 2017).

3.3 Government Programs

Currently, there is very little direct government support for BECCS projects anywhere in the world. That said, there are several programs related to bioenergy and to fossil CCUS that can support BECCS projects both directly and indirectly. For example, bioenergy R&D programs and commercialization incentives can increase supply of biogenic emissions for future BECCS projects, and CCUS programs aimed at fossil-fueled power and/or industrial systems can help reduce the costs of both capture and storage for BECCS projects. For example, bio-CCS research has been funded through the EU Framework Programme for Research and Innovation's Horizon 2020 Program since 2014.

It is through these existing bioenergy and/or CCUS government programs that BECCS projects have gained support to date. For example, in the United States, the ADM ethanol BECCS project in Decatur, IL, has secured funding from the DOE's existing CCUS program (Massachusetts Institute of Technology, 2016) and has recently received additional funding to explore further ethanol capture and saline storage demonstrations (Lusvardi, 2016). In Norway, the Klemetsrud partial-BECCS facility at a municipal solid waste plant is receiving support from the City of Oslo government (Engen, 2016) and the Ministry of Petroleum and Energy through the CLIMIT program.

In addition, there have been a number of proposed government programs in the United States that would support BECCS projects. The most important of these proposed incentives is an expansion of section 45Q in the U.S. tax code that increased tax credits to \$50/tCO_2 for saline storage and \$35/tCO_2 for utilization, which could lead to increased ethanol BECCS projects for both EOR and saline aquifer storage in the U.S. (NEORI, 2016). In addition, the California Air Resource Board (ARB) is in the process of determining how CCUS can contribute towards the state's cap-and-trade and low carbon fuel standard regulations, both of which could drive BECCS projects (CEPA, 2016). Lastly, there was language in the version of the Energy Bill passed by the U.S. Senate in 2016 that authorized \$22M/yr for five years to support a partial BECCS co-fired biomass + coal power project in the southeastern United States (CCR, 2016), and the U.S. Department of Energy's Advanced Projects Research Agency-Energy (ARPA-E) has also explored launching a program dedicated to BECCS innovation in the near future (Stark, 2016).

3.4 Market Drivers for BECCS Deployments (e.g., Policies, Regulatory, etc.)

The most significant driver for BECCS projects today is policy support. In particular, government incentives for biofuels and/or CCUS are critical for making BECCS projects economic. This is because biofuels are currently more expensive than fossil fuel alternatives in most markets globally, and markets for compressed CO_2 are relatively small and low-priced.

In the United States, EOR can help drive some demand for ethanol BECCS projects to a moderate degree. However, ethanol facilities will need to address challenging economics in the near future with oil prices and relatively small volumes compared to the needs by EOR operators, although the 45Q tax credits and credits for low carbon fuels such as in California can help to drive additional BECCS projects. There is some niche demand for CO_2 from biogenic sources in food and beverage and other manufacturing applications, but the potential to drive new, large-scale BECCS projects using this demand source is limited. Increased demand for CO_2 utilization in novel applications such as cements, plastics, etc., is also unlikely to drive many BECCS projects outside of the ethanol industry, given the lower-cost and widespread availability of CO_2 from fossil-fueled anthropogenic sources.

On the regulatory side, there are several ongoing efforts in the United States that could help advance BECCS projects. For one, clarifying the U.S. Environmental Protection Agency's (EPA) Class VI underground injection permitting process and/or approving state primacy applications could help advance projects both on the fossil and biogenic capture side. To date, there are very few Class VI permits that have been issued by the U.S. EPA.

Corporate demand for BECCS projects is also very low. Awareness of the value of BECCS among corporate buyers of renewable energy is low, and these buyers are often constrained to purchase market-competitive contracts, which BECCS projects are unlikely to deliver in most locations. The biggest potential hurdle with BECCS projects for corporate buyers is on the GHG accounting side. Without widely accepted biofuel and CCUS accounting frameworks, corporations are exposed to negative public perception of BECCS as an effective climate strategy. Having wide-scale acceptance of GHG accounting protocols for the sustainable growth of biofuels and the long-term safe and reliable geologic sequestration of CO_2 are critical for boosting corporate demand for BECCS projects.

Lastly, finance is an important factor for BECCS projects. The cost of capital is high for early generation BECCS projects, given technology and regulatory uncertainty, as well as the variability inherent in standard CO_2 off-take agreements (as CO_2 suppliers sell to EOR operators on an oil-priced-indexed contracts). To address these concerns, regulatory programs such as loan guarantees, extending master limited partnership (MLP) tax structures for BECCS projects, and offering government-backed price-stabilization contracts for CO_2 off-take can enable faster and wider market adoption of BECCS projects.

3.5 Barriers to Large-scale BECCS Demonstration and Deployment

There are many barriers to large-scale BECCS deployment. This section provides a brief discussion of where challenges exist and some ways of overcoming them.

3.5.1 Technical

Some of the technical barriers are related to the biomass combustion/conversion process, e.g., dealing with the high moisture content, diversity, variability, and impurities of biomass, which can lead to increased corrosion, slagging, and fouling (Pourkashanian, et al., 2016). Further, biomass co-firing in excess of 20% requires increasing levels of biomass pre-treatment and boiler modifications (Gough and Upham, 2010).

Despite these challenges, BECCS applications are among the most mature technologies in the NET portfolio and allow for a relatively smooth integration into current energy systems. Research, development, and demonstration (RD&D) into the less mature options, like large scale biomass gasification, should be pursued. Research is needed to identify feedstocks that require limited processing, compatibility with existing boiler and pollution control equipment, and reduction in processing equipment costs, and associated energy costs. The specific processes adapted to every biomass source (vegetal, waste, etc.) and use (power and heat, paper, cement, etc.) require a considerable amount of research focusing on the heat integration of the capture unit, which is so important for the overall efficiency and costs of capture.

3.5.2 Economics and Incentives

Despite the relatively robust technical potential of several BECCS options that vary from 3-20 $GtCO_2$/yr uptake (Azar, et al., 2010; Woolf, et al., 2010; IEAGHG, 2011; IEAGHG, 2013; McLaren, 2012; van Vuuren, et al., 2013; Arasto, et al., 2014; Caldecott, et al., 2015; NRC, 2015), the economic potential lags. Considering the cost of resources relative to a fossil fuel reference technology, the economic potential is often only a fraction of the technical potential.

In this regard, price, reliability and sustainability of biomass supply will have a profound effect on the eventual economic feasibility of BECCS. Current economic assessment uncertainties make it difficult to predict which sectors/applications will be able to deploy BECCS in the most profitable way. Small-scale BECCS in the power sector will likely increase electricity costs (IPCC, 2005). Currently, CO_2 price signals are weak and there is no incentive for CCUS or even BECCS. In addition, land and biomass supply limitations could cause a substantial increase in BECCS costs when the biomass removal rate reaches large-scale deployment, i.e., about 12 $GtCO_2$/yr (Kriegler, et al., 2013; Lackner, 2010). Financing BECCS projects continues to be difficult because there are not enough operational large-scale, whole-chain projects that could provide the necessary investor confidence.

Bioenergy incentives have the potential to lead to land conversion and result in LUC and related emissions (Wise, et al., 2009; Reilly, et al., 2012) if biomass production does not adhere to sustainability standards. Finally, BECCS deployment could suffer from other limitations, especially when competing with low-cost sustainable biomass feedstocks, confronted with limiting land resources, affordable CO_2 storage capacity and funding/investment resources.

To overcome these economic obstacles, there is an urgent need for financial mechanisms and incentives to promote the benefits associated with BECCS. Many studies identified setting a price of CO_2 as one of the main drivers for BECCS deployment (IEAGHG, 2011; IEAGHG, 2013). An advantage of BECCS, and other NETs, is to compensate for residual emissions from sectors where abatement is more expensive. Along those lines, a BECCS plant in the power sector might provide a double benefit: producing low-carbon electricity and negative emissions at the same time (Dooley, 2012). Economies of scale can bring down the cost of BECCS substantially (IPCC, 2005) and for some industrial sectors, BECCS might be the decarbonisation option with the lowest cost (Meerman, et al., 2013). Integrated assessment models (IAMs) project that carbon abatement will be significantly costlier if NETs, especially BECCS and DAC, are unavailable (Rose, et al., 2013). In addition, BECCS technologies allow for overshoot scenarios, which postpone the costs of mitigation, i.e., it presents a financial opportunity for discounting (Azar, et al., 2013; Lomax, et al., 2015). IAMs themselves need improvement and refinement to represent BECCS pathways adequately (The Secretary of Energy Advisory Board (SEAB) Task Force on CO2 Utilization, 2016).

Early opportunities for BECCS are co-firing of biomass in fossil-CCUS plants and bioethanol plants (Gough and Upham, 2010; Lomax, et al., 2015). Currently, co-firing biomass in heat and power plant appears to be the most efficient way in terms of GHG reduction targets in a cost-effective manner (REN21, 2013; Junginger, et al., 2014 Sterner and Fritsche, 2011). When several BECCS project are co-located, the cluster structures with shared infrastructure provide huge opportunities not only for BECCS but also for CCUS deployment in general.

3.5.3 Policies, Regulations, and Accounting

Many low-carbon policies and GHG accounting frameworks do not appropriately recognise, attribute, and reward BECCS and negative emissions in general, especially regional cap-and-trade schemes (IEAGHG, 2014; Zakkour, et al., 2014). As a result, there are no incentives to capture and store biogenic emissions over zero emissions, e.g., from dedicated biomass firing without CO_2 storage. The political processes involved in designing accounting schemes are complex and the timelines lengthy, interfering with a rapid implementation of BECCS. Without strong policy support, weak or patchy GHG accounting rules can lead to carbon leakage and undermine the potential for BECCS and other technological solutions to be considered negative emissions technologies and more broadly, the potential carbon neutrality of bioenergy. Even when those would be aligned, the direction and immediacy of returns remains a challenge. For example, long growth times of biomass could delay return of revenues, thus acting as a disincentive for BECCS projects, especially if other options with faster returns are available (e.g., renewables) (Thomas, et al., 2010).

Incentivising the double benefit of BECCS can help avoid direct investment competition with other abatement options. Concerted efforts, e.g., global forest protection policies, carbon stock incentives, and bioenergy/renewable energy incentives, are necessary to avoid undesirable LUC emissions (Wise, et al., 2009; Clarke, et al., 2014). Large-scale bioenergy development, together with strict forest management, can increase food and water prices by exacerbating land competition (Popp, et al., 2011). Thus, forest and land management activities can be optimized to address multiple-use scenarios. In addition, different policies can have diverse impacts on CO_2 prices, food prices, electricity prices, and GHG emissions (Sands, et al., 2017).

The European Directive on the geological storage of CO_2 (2009/31/EC), known as the 'CCS Directive', has established a legal framework for the geological storage of CO_2. Potential BECCS projects fall under this Directive and must follow the four Guidance Documents (GDs) that have been produced (EU, 2016).

A variety of approaches have been implemented to enable carbon markets. For example, clean development mechanism (CDM), joint implementation (JI), and emission trading systems (ETS) are a few examples of functioning carbon markets that have been moderately effective (Smith, et al., 2014). Several studies show that the CDM can provide significant incentives for renewable energy deployment in developing countries, including BECCS (Restuti and Michaelowa, 2007; Bodas Freitas, et al., 2012; Hultman, et al., 2012). However, direction and timing of returns need to be addressed at the same time to avoid project failures.

3.5.4 Public Perception

Public perception of BECCS is influenced by two main parts: 1) image of biomass/bioenergy and 2) CCUS. Bioenergy, as a renewable energy, and especially if produced from biomass waste, tends to be seen mostly favourable. Biomass for bioenergy is seen as competing with food supplies land use, while half of the population think the land can be used more productively (ETI, 2016). Public perception of BECCS varies with location and social/cultural background and it can be either a driver or a barrier. The public perception of CCUS is well studied (e.g., Ashworth, et al., 2013; Dowd, et al., 2014) but research focussing on BECCS is limited. BECCS generally has a lower profile than fossil-CCUS and appears to lack support among external as well as its own stakeholders (Dowd, et al., 2015). When competing with other mitigation options, such as other renewable energy and energy efficiency, fossil-CCUS and BECCS are usually perceived as non-favourable (TNS 2003). The negative public perception of CCUS can adversely affect BECCS (Mander, et al., 2011). In fact, public opposition has led to several CCUS and bioenergy projects being cancelled in the past.

To overcome these issues, BECCS project developers and advocates should focus more on building up trust with the general public and local communities via dialogues and site visits (Upham and Roberts, 2010) instead of just providing educational information. Stronger collaboration and exchange of ideas between stakeholders of the CCUS, bioenergy, and BECCS industries would also be beneficial.

3.5.5 Land Demand and Land Use Change (LUC: dLUC and iLUC)

A critical issue related to sustainable bioenergy production for BECCS is LUC. Direct LUC (dLUC) is a change in the use or management of land caused by humans that leads to a change in land cover (IPCC, 2000). Indirect LUC (iLUC) means a change in land use triggered by diversion of land to replace another product or service (IPCC, 2014).

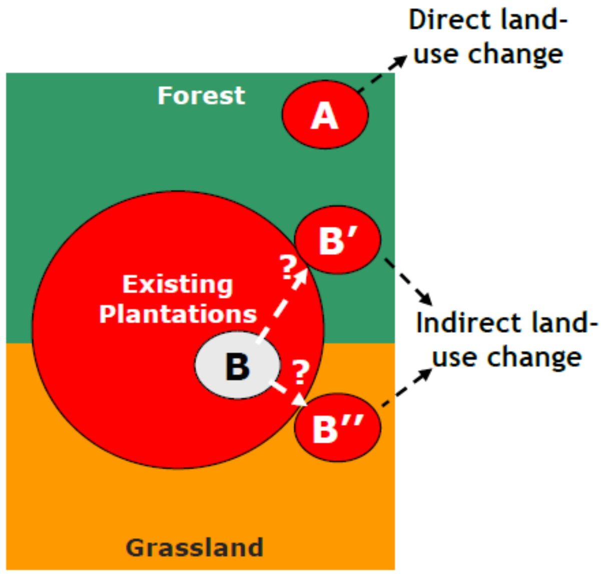

Figure 3: Concept of direct and indirect land use change (Hamelinck, 2014)

dLUC occurs when additional biomass feedstock demand leads to the cultivation of new areas (see circle A in Figure 3) for biomass production. iLUC, in contrast, can occur when existing production areas cover the additional feedstock demand (see B), displacing the previous production function of the land, which can trigger expansion of land to new areas (e.g., to B' and/or B''). The balance between LUC and association emissions is critical as it may render any zero emissions, negative emissions, or double benefit assumption invalid (Kemper, 2015). Additionally, the time delay between carbon emission and carbon uptake by natural systems (plants, soils, and oceans) makes it difficult to calculate the carbon balance.

To limit the negative effects of LUC and land competition for bioenergy with land for crops, BECCS can use semi-perennial crops, perennial grasses or woody biomass that need less fertiliser and grow on marginal or carbon-depleted land (Harper, et al., 2010; Sterner and Fritsche, 2011; Sochacki, et al., 2012). For example, miscanthus outperforms yields and GHG savings of switchgrass and corn, and can grow on low-quality soil (Brandao, et al., 2011; Dwivedi, et al., 2015). Other means to avoid or reduce LUC emissions are the use of sustainable biomass, wastes/residues and 2nd generation crops (Davis, et al., 2011; Scown, et al., 2012).

3.5.6 Resource Limitations

In the end, BECCS and other bioenergy applications might experience a limitation of feedstock to truly "additional" biomass. "Additional" refers to biomass that does not negatively affect sustainability and food security and includes e.g., winter cover crops, timber processing wastes, urban waste wood, landfill wastes, and forest/crop residues (Searchinger and Heimlich, 2015). It also includes only biomass grown in excess of that which would be grown anyway or biomass that would otherwise decompose (EEA, 2011). In addition, there might be competition for biomass and land resources between several sectors/players and competition for CO_2 storage resources between different mitigation options (Clarke, et al., 2014; Gough and Upham, 2010; Gough and Upham, 2011; McLaren, 2012).

Early BECCS projects should aim to use mainly “additional” biomass and 2[nd] generation biofuel crops to avoid adverse impacts on land use and food production (Smith, et al., 2014). However, additional biomass is likely to be costlier due to, for example, increased irrigation. BECCS options that optimize water use and carbon footprint need to be identified through careful selection of crops, location, cultivation methods, pre-treatment processes, and biomass conversion technologies. Sustainable biomass feedstocks will require avoidance of unsustainable harvesting practices, e.g., exceeding natural replenishment rates (IPCC, 2014b). Using “additional biomass” to avoid sustainability issues also helps improve public acceptance (Searchinger and Heimlich, 2015).

3.5.7 Supply Chain Development

Lack of infrastructure (i.e., for biomass, natural gas, and CO_2 as well as CO_2 storage/utilization) could be a showstopper for BECCS projects. BECCS already depends on CCUS scalability, deployment, infrastructure, and timeframe, which could be up to half a century for a CCUS roll-out of 8-16 $GtCO_2$ (Azar, et al., 2010). The timeline for CCUS deployment could be the most important cost barrier for BECCS (Edenhofer, et al., 2010; Tavoni, et al., 2012; Krey, et al., 2014; Kriegler, et al., 2014; Riahi, et al., 2014). Large-scale biomass supply chains and trade need further development.

Sustainability needs to be ensured across the whole BECCS chain. Improving pre-treatment processes for biomass (i.e., densification, dehydration, and pelletisation) will make biomass transport more efficient and remove geographical limitations of biomass supply (Hamelinck, et al., 2005; Luckow, et al., 2010).

3.5.8 Other Issues in the Food-Water-Energy-Climate Nexus

The food, energy, water nexus interacts with climate and assessing these interactions will likely necessitate new and integrated approaches. General barriers associated with BECCS include impacts on emissions from LUC, competition for land with other services, water demand and biodiversity (Kemper, 2015). One issue of great concern is how to avoid food price increases due to land use competition. However, there is a multitude of other factors that influence food prices (e.g., fossil fuel prices, stockpiles, demand, speculation, trade liberalisation, subsidies, climate change, weather, currency fluctuations, inflation, social unrest) and the complexity of the food system make it difficult to predict the influence of increasing bioenergy crops. Bioenergy applications require disproportionately high amounts of water, especially when compared to other energy production options (WEC, 2010). As water becomes more limiting, questions about water allocation are likely to become central. Irrigation of bioenergy crops is likely to be very costly and to compete with other uses. In addition, fertiliser use might negatively affect the economics of BECCS (Crutzen, et al., 2008) and offset the CO_2 emissions reductions through an increase in N_2O emissions (Robertson, et al., 2000; Brown, et al., 2004; Li, et al., 2005; Smith, et al., 2012). Furthermore, particulate matter (PM) emissions of biomass co-firing are significantly higher than of dedicated coal combustion (NETL, 2012, Schakel, et al., 2014).

Improvements in crop yield increases, food waste reduction, and demand side changes could help free land for bioenergy production (Thomson et al., 2010). Increased PM emissions of BECCS can be addressed through optimal design of the whole BECCS chain, e.g., improvement of the biomass pre-treatment and transport processes, especially via fuel switching.

4 Overview of BECCS Technology Options and Pathways

4.1 Power Generation

The power generation economic sector emitted, which is comprised of the electricity and heat production industry, is a large contributor to global CO_2 emissions (Figure 4). Fossil fuel based steam power generation plants typically burn conventional hydrocarbon-based fuels such as coal, gas, and oil to create steam to drive the turbines that produce electricity. Biomass firing and co-firing with conventional fuels can substantially reduce GHG emissions in the production of electric power (IRENA, 2012). In general, there are three pathways for the use of biomass as fuel for power generation plants (IEA, 2012):[1]

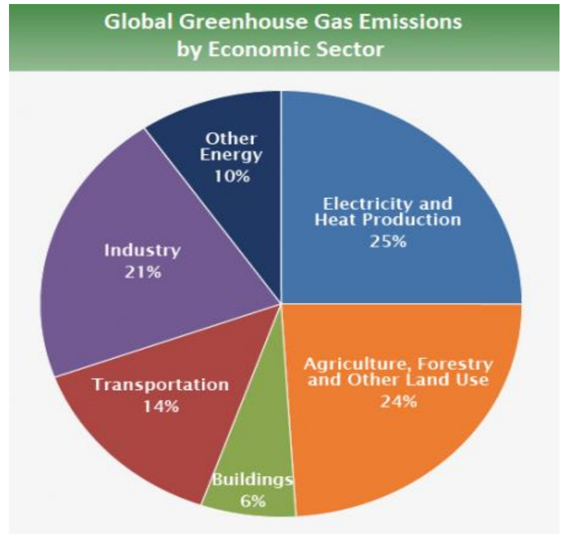

Figure 4: Source: EPA Global Greenhouse Gas Emissions Data. IPCC (2014) based on global emissions from 2010. Details about the sources included in these estimates can be found in the *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

- Development of new power generation plants that utilize biomass. The plants can involve combustion or gasification of biomass. The combustion plants typically require designs that use grate-fired or fluidized bed boilers. Gasification of biomass can occur using a gasifier producing a syngas that is used for combustion in a boiler of gas turbine.
- Co-firing of biomass with a conventional fuel such as coal at an existing or new power plant.
- Conversion of an existing pulverized coal boiler in a coal plant to instead burn biomass.

CCUS technology can be added to biomass or co-fired plants to capture CO_2 emissions from the power generation. A BECCS power plant involves the use of biomass as fuel and may utilize pre-combustion, post-combustion, or oxy-fuel technology in the capture of CO_2. BECCS technology applications in the steam power generation sector fall into 2 categories: 1) Combustion & Co-Firing and 2) Thermal Gasification.

4.1.1 Combustion & Co-Firing

Fuels

The burning of hydrocarbon fuels with oxygen in combustion boilers to create steam and electricity results in substantial CO_2 and GHG emissions. Coal-based electrical generation in the United States represented approximately one-third of the total U.S. generation and more than 70% of CO_2 emissions emitted by the power generation sector in 2015 (USEIA, 2016; Figure and Figure 66). In 2016, the use of natural gas surpassed coal as the primary fuel source in the U.S. power generation sector. Globally, coal is the second largest energy source as stated by the International Energy Outlook (EIA, 2016). The top three coal-consuming countries are China, the United States, and India, which together account for more than 70% of world coal use (EIA, 2016). In the United States, total CO_2 emissions from combustion power plants have been estimated to be 1,925 million metric tons, or about 37% of the total U.S. energy-related CO_2 emissions (5,271 million metric tons) in 2015 (EIA, 2016). Increasing the use of biomass and co-firing of biomass in pulverized coal power plants for electricity production has the potential to reduce overall GHG from the power sector.

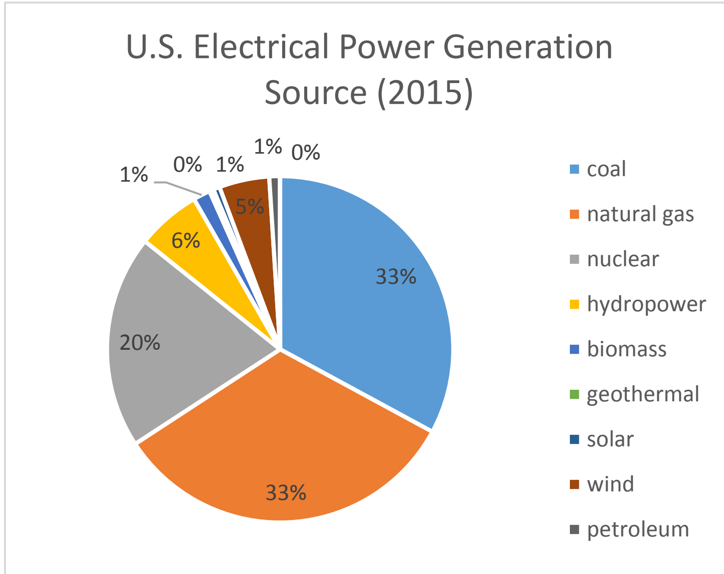

Figure 5: U.S. Electrical Power Generation Sources (EIA, 2016)

Biomass has been successfully used to supplement pulverized coal, but the use of biomass currently represents a very small portion of overall electricity generation in the United States (EIA, 2016). Other countries with large forestry reserves, such as Finland, utilize biomass for electricity generation to a greater extent (Karhunen, Ranta, Heinimö, & Alakangas, 2014). The biomass industry supplies about 52 gigawatts of global power generation capacity, mostly using wood products, municipal solid waste, and agricultural

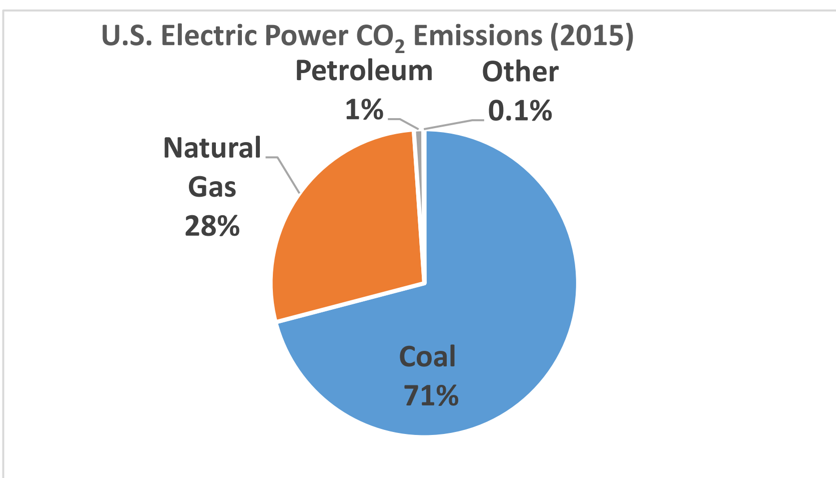

Figure 6: Carbon Dioxide Emissions from US Electric Power Plants

waste (Block, 2009). The United States supplies approximately 20% of the world's biomass for power production (Shah, 2011) and a substantial portion of the wood pellets from the United States are used to fuel the Drax Power station in the United Kingdom (IER, 2015).

The preferred biomass fuel for use in pulverized coal-fired boilers is pelletized wood, including wood chips, pellets, and sawdust, which are combusted or gasified to generate electricity (WBDG, 2016) as depicted in Table 3.

Table 3: Biofuel Types (IEA, 2016)

Agricultural	Forestry products	Domestic and municipal wastes	Energy crops
Harvesting residues • Straws • Corn stalks	**Harvesting residues** • Forestry residues	**Domestic / industrial** • MSW / RDF/ SRF • Scrap tyres • Wood wastes • Sewage sludges	**Wood** • Willow • Poplar
Processing residues • Rice husks • Sugarcane bagasse • Olive/palm oil/sunflower husks and residues • Fruit residues • Cereal straws and residues	**Primary Processing residues** • Bark • Sawdusts • Offcuts • Wood pellets	**Urban green wastes leaves** • Grass and hedge cuttings	**Grasses etc.** • Switch grass • Reed Carry Grass • Miscanthus
Animal wastes • Poultry litter • Tallow • Meat and bone meal	**Secondary process wastes** • Sawdusts • Offcuts		

The use of torrefaction, a process in which the biomass fuel is heated between 200°C and 300°C in the absence of oxygen and converted into char, has been successfully implemented to improve biomass feedstock characteristics (IEA, 2012). Typically, torrefaction of wood results in pellets that have 25-30% higher energy density than conventional wood pellets (IEA, 2012). The product has properties closer to those of coal, with similar handling, storage, and processing.

Combustion

Biomass Combustion Power Plants

Several power generation plants using biomass as the primary energy source are operating worldwide. Typical biomass power plant sizes are based upon availability of local feedstocks and range between 10 and 50 MWe in size (IEA, 2012). However, converted pulverized coal power plants that utilize 100% biomass fuels are much larger. The power generation efficiencies of plants in the 10-50 MWe size without CCUS range between 10-33%, lower than plants that burn natural gas or coal (IEA, 2012).

Biomass combustion produces acid gases such as sulfur oxides (SO_X), nitrogen oxides (NO_X), and hydrogen chloride (HCl) but at levels that are lower than those for most coals. However, the flue gas must still be treated with conventional particulate control equipment. The use of limestone injection in the boiler fluidized bed and typical wet, lime, or limestone based flue gas desulfurization technology is used to capture sulfur dioxide and hydrogen chloride. NO_X emissions are controlled using low NO_X burners, two stage combustion, selective catalytic reduction (SCR), and selective non-catalytic reduction

(SNCR) similar to plants that are burning coal as fuel. Trace metals such as mercury are present in flue gas from biomass plants at levels dependent upon the type of biomass that is used. Mercury emissions can be reduced when co-firing with biomass if halogens are present in the biomass. (Cao, et al., 2008). In general, biomass such as wood has lower mercury levels as compared to coal (Rohr, et al., 2013), (Tweed, 2013) and will result in lower mercury emissions. Other biomass fuels such as poultry litter that could be used in co-firing, for example, can contain higher levels of lead, arsenic, copper, iron, zinc, and mercury and may require additional treatment when used as a biofuel in power generation applications (Ewall, 2007).

Fuel Unloading & Storage

The biomass fuel (wood chips, sawdust, or pellets) storage system at a power generating facility will typically use both a bunker for short-term storage and an outside fuel yard for larger storage. Bulk handling and conveying equipment with pneumatic transport and other equipment including control system, stackers, dust collection, bins, bucket elevators, reclaimers, front-end loaders, and augers are used to store and transfer the biomass fuel from the unloading area to the mills.

Combustion / Steam Turbine

Wood chip-fired electric power systems generally consume approximately one dry ton of biomass per megawatt-hour of electricity production (WBDG, 2016). This is a high-level approximation typical of wet wood systems and the actual value varies with system efficiency. For comparison, this approximation is equivalent to 20% HHV efficiency with 17 MMBtu/ton wood (WBDG, 2016).

In a direct combustion system, biomass is burned in a combustor or furnace to generate hot gas, which is fed into a boiler to generate steam. The steam is then expanded through a steam turbine or steam engine to produce mechanical or electrical energy.

Typical biomass boilers are the stoker or fluidized bed type (WBDG, 2016). Stoker boilers burn fuel on a grate to produce hot flue gases that are used to produce steam. The ash from the combusted fuel is removed continuously (WBDG, 2016). Fluidized bed boilers suspend fuels on upward blowing jets of air during the combustion process. Circulating fluidized bed boilers (CFB) separate and capture fuel solids entrained in the high velocity exhaust gas and return them to the bed for complete combustion (WBDG, 2016).

Biomass Co-firing

The co-firing of biomass at pulverized coal power generation plants is well established and cost-effective (IEA, 2016). Biomass co-firing equipment can be installed with relatively minor modifications and capital investment to an existing pulverized coal plant. The addition of storage, drying, pre-treatment, and feed systems can be done at a relatively low cost. The use of biomass co-firing provides co-benefits in reducing flue gas cleaning as acid gases such as SO_x, HCl, and NO_X are typically reduced in the flue gas (IEA, 2016).

Different approaches to co-firing of biomass at pulverized coal power plants that have been used at several locations in North America and Europe (IEA, 2016):

- Milling of 100% biomass through one or more of the existing coal mills and firing systems involves modification to both the plant milling and firing systems (IEA, 2016). The approach involves firing of both coal and biomass, each from dedicated systems, into the boiler.
- Pre-mixing of the biomass and coal in the coal handling and conveying system, with use of the existing milling and firing systems, is the simplest design and requires 5-10% biomass with coal (IEA, 2016).
- Milling of the biomass to sizes suitable for suspension firing and the direct injection in the pulverized coal firing system results in the highest capital cost investment, but results in greater co-firing ratios. Biomass can be co-fired with the coal based upon heat input (IEA, 2016).
- Gasification of the biomass in a separate gasifier to form a gas which is combined with air and injected into the pulverized coal boiler for combustion (IEA, 2016).

Biomass Co-firing Projects

The successful demonstration of biomass co-firing has reduced the technical risk and improved the technology dramatically. Co-firing ratios of biomass to coal have ranged between 5-50% (IEA, 2016). In Europe, electricity generation from biomass peaked between 2005-2006 due to government subsidies (IEA, 2016) and again between 2010-2012. But without subsidies, a sharp reduction in electrical generation with biomass can occur, as it did in the Netherlands (IEA, 2016).

Table 4: Worldwide Biomass Projects (Source: IEA, 2016)

Power Station	Country	Unit	Owner	Plant Output (MWe)	Plant Output (MWth)	Direct Co-firing percentage (heat)
Studstrupvaerket	Denmark	4	Dong Energy	350	455	7
Studstrupvaerket	Denmark	3	Dong Energy	350	455	0-100
Amagar	Denmark	1	HOFOR	80	250	0-100
Avedore	Denmark	1	Dong Energy	215	330	100
Avedore main boiler	Denmark	2	Dong Energy	365	480	100
Avedore straw boiler	Denmark	2	Dong Energy			100
Grenaa Co-Generation Plant	Denmark	1	Verdo (from 2017 Grenaa Vermevaerk	19	60	50
Herningvaert	Denmark	1	Dong Energy	95	174	100
Randers Co Gen Plant	Denmark	1	Verdo	52	112	100
Ensted biomass boilers	Denmark	3	Dong Energy	630	95	100
Skaerbaekvaerket	Denmark	3	Dong Energy	392	444	100
Maasvlake	Netherlands	1	E.On	531	-	10
Maasvlake	Netherlands	2	E.On	531	-	10

Power Station	Country	Unit	Owner	Plant Output (MWe)	Plant Output (MWth)	Direct Co-firing percentage (heat)
Amer Centrale	Netherlands	8	Essent	600	250	10-12
Gelderland	Netherlands	13	Electrabel	602	-	25
Borssele	Netherlands	12	EPZ	403	-	10-15
Amer Centrale	Netherlands	9	Essent	600	350	27 + 5
Drax Power	United Kingdom	1-3	Drax Power Group	TBD	TBD	TBD
Ironbridge Power Station	United Kingdom	TBD	TBD	TBD	TBD	TBD
Tilbury Power Station	United Kingdom	TBD	TBD	TBD	TBD	TBD
New Hope Power Partnership	United States	1	NHPP	140	-	100
Les Awirs	Belgium	TBD	TBD	TBD	TBD	TBD
Atikokan Generating Station	Canada	TBD	Ontario Power Generation	TBD	TBD	TBD
Thunder Bay Generating Station	Canada	TBD	Ontario Power Generation	TBD	TBD	TBD
Port Hawkesbury	Canada	TBD	Nova Scotia Power	TBD	TBD	TBD

Notes:

1. **This is a partial list**
2. **Several projects have been taken out of service in 2016-2017**
3. **Capacity is included in the figure for the main boiler**
4. **From 2017**
5. **Conversion to pellets decided in 2015**
6. **Biomass boilers supplied steam corresponding to 40 MWe out of block unit total 630 MWe**
7. **Biomass boilers to supply steam corresponding to 90 MWe and 320 MWth out of this from 2017**

Large Coal Conversion to Biomass Combustion Power Plant Projects

Several successful demonstrations of pulverized coal power generation plants converted to 100% biomass plants exist today (IEA, 2016). The Drax Power (Drax Group) plant in Yorkshire, UK, completed a conversion of three 660 MWe pulverized coal units to 100% biomass wood pellet fuel during the period of 2010-2015 (IEA, 2016). The project included a significant upgrade to include biomass reception, storage, and handling, allowing up to 9 million tonnes of biomass per year (IEA, 2016).

Though now closed, the Ironbridge Power Station located in Shropshire, England, is owned by E.ON. The plant includes two 500 MWe pulverized coal-fired units and was successfully converted to 100% biomass in 2013 (IEA, 2016). The Tilbury power station near London, England, converted three 300 MWe pulverized coal boilers to biomass wood pellet fuel for approximately 2 years prior to closure (IEA, 2016). In Belgium, the 80 MWe Les Awirs plant and the 250 MWe Max Green plant were both converted from coal to 100% biomass. The DONG Energy Avedore Unit 1 & 2 plant in Denmark was converted to 100% wood pellet biomass in 2014 (IEA, 2016).

In North America, Canada has installed 61 bioenergy plants with a total of 1,700 MWe generating capacity (IEA, 2016). The Ontario Power Generation (OPG) Atikokan Generating Station was converted from a pulverized coal plant and is now the largest power generation facility in North America using 100% biomass with generating capacity of 200 MWe. The OPG Thunder Bay Generating Station was converted from coal to advanced biomass in February, 2015 (IEA, 2016).

In the United States, biomass is used primarily in co-generation plants for the pulp and paper industry (Haq, 2002). However, one exception is the New Hope Power Partnership plant located in Tampa, Florida (Power Technology, 2014). The New Hope Power Partnership biomass power plant burns sugar cane and wood and has electrical generating capacity of approximately 140 MWe (Power Technology, 2014).

4.1.2 Thermal Gasification

Similar to coal, biomass can be utilized in a thermal gasification process (Figure 7) in which solid feedstock is transformed into a combustible synthetic fuel gas containing hydrogen (IEA, 2012). The

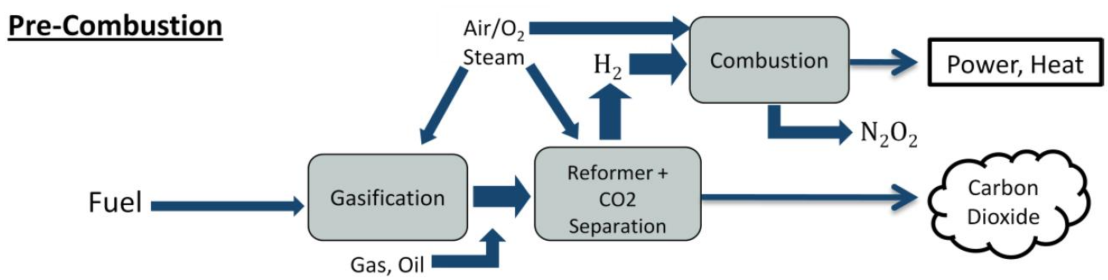

Figure 7: Pre-combustion steps (Source: Global CCS Institute: Global Status of BECCS Projects 2010)

synthetic gas with hydrogen can then be used to produce electricity with gas combustion turbines at higher efficiency than with a turbine in a steam cycle (EERE, 2017). The process involves heating the biomass with less oxygen than is needed for complete combustion. The gasification process involves operation at high temperatures (>700°C) with a defined amount of oxygen and/or steam to convert the biomass into carbon monoxide, hydrogen, and carbon dioxide (EERE, 2017). The carbon monoxide then reacts with water (steam) to form carbon dioxide and additional hydrogen using a water-gas shift reaction. Separation of the hydrogen from this gas stream is performed leaving a pure stream of carbon dioxide. The gasification of biomass does not occur as easily as with coal and an extra reforming step is needed in the presence of a catalyst to reform the remaining hydrocarbon compounds that have not been fully converted. Another shift reaction with steam again converts the produced carbon monoxide to carbon dioxide.

New developments in biomass power generation include the biomass integrated gasification combined cycle (BIGCC) concept. Further research in this area is needed to determine optimal efficiency. In addition, the Vaskiluodon Voima Oy power generating plant in Finland is one of the largest bio-gasification plants (140 MWe) to produce a gas that is burned in the existing power plant pulverized coal boiler to reduce coal consumption by approximately one half.

Pyrolysis

Pyrolysis is a process in which the biomass is heated to 400°C and 600°C in the absence of oxygen (IEA, 2012). The products of pyrolysis are charcoal, liquid pyrolysis oil, and a product gas which can be used in the heat and power generation plants. Further work to determine whether mixing of the pyrolysis oil with conventional crude oil in refineries is feasible (IEA, 2012).

4.2 Fuels and Chemicals Production

4.2.1 Ethanol/Fermentation processes

The global consumption of fuels and chemicals is steadily rising. Currently, there are over 60 bio-refinery projects around the world producing alcohols, hydrocarbons, and intermediate chemicals from biomass like 1,4-butanediol (BDO) (Warner, Schwab, & Bacovsky, 2016).

Global demand for biofuels grew at 5% per year between 2010 and 2015. It is projected to further grow at 3.6% per year over the next two decades (74.2 million tonnes of oil equivalent (MTOE) in 2015 to 129.7 MTOE by 2035). Global demand for ethanol grew at 5.6% per year from 2011 to 2014 (BP, 2017). Ethanol and bio-butanol represent a significant part of that demand growth (BP, 2017). Ethanol is commonly made by fermenting sugars from agricultural feedstocks such as corn, beets, and sugar cane or through gasification of biomass and converting the syngas to ethanol by catalytic or bio-based approaches (e.g., LanzaTech's gas-to-ethanol technology). Further, ethanol can also be made from lignocellulosic feedstock such as woodchips, short-rotation woody crops, grasses, sugarcane bagasse, and corn stover.

The steps in producing ethanol from corn include grinding the feedstock to a coarse flour (meal), cooking the meal into a hot slurry, and adding enzymes to produce a "mash"; and fermenting the mash by adding yeast to produce ethanol, CO_2, and solids from the grain and yeast, known as fermented mash. The fermented mash is distilled to produce ethanol and water, and a residue called "stillage". The ethanol is distilled to remove the water and the co-products include distiller's grains, CO_2, and soluble syrup. Capturing CO_2 from fermentation is relatively facile compared to separating CO_2 from power plant flue gases because the fermentation gas stream is almost pure CO_2.

Cellulosic ethanol is mainly made by acid or enzymatic pre-treatment of the woody biomass, followed by using enzymes to convert the complex polysaccharides to simple sugars and fermenting the simple sugars to ethanol, producing CO_2 and solid fuel (lignin). Fermentation from corn-ethanol plants represents the largest single-sector CO_2 source for the U.S. CO_2 market. The CO_2 is sold and utilized in the beverage industry, to create dry ice, in metal welding, the production of chemicals, pH reduction, EOR, and CO_2 in hydraulic fracturing applications. Raw CO_2 from ethanol fermentation contains trace sulfur compounds and acetaldehyde that must be removed before the gas is supplied for CO_2 utilization or storage. Typical corn-ethanol plants in the United States can supply approximately 390 to 725 tonnes of CO_2 per day (Rushing, 2015) and CO_2 sourced from corn-ethanol plants can displace sources with higher emissions and/or capture costs (Mueller, 2017). There are around 210 ethanol plants in the United States that together are emitting an estimated 100,000 T CO_2/d (Wittig, 2016). Of these, CO_2 is stored or used for EOR at three plants:

- The ADM Decatur plant currently injects CO_2 to a saline aquifer for storage, previously injecting approximately 1 million tons of carbon over 3 years and now has the capability to store 1.1 million tons of carbon annually,
- The Bonanza BioEnergy CCUS EOR project in Garden City, Kansas (Conestoga Energy) captures ~100,000 T/y for EOR. At the Bonanza BioEnergy project, the raw fermenter gas contains more than 99% CO_2 and is dehydrated, compressed to 1500 psi and transported 15 miles to an oilfield where it is injected at depths around 4800' (Wittig, 2016),
- Conestoga Energy Holdings' Arkalon ethanol plant near Liberal, Kansas produces ~269,000 T/y (14 MMCF/d) CO_2 for EOR (Texas, Oklahoma panhandles).

4.2.2 Synthesis Processes (e.g., Fischer-Tropsch [FT])

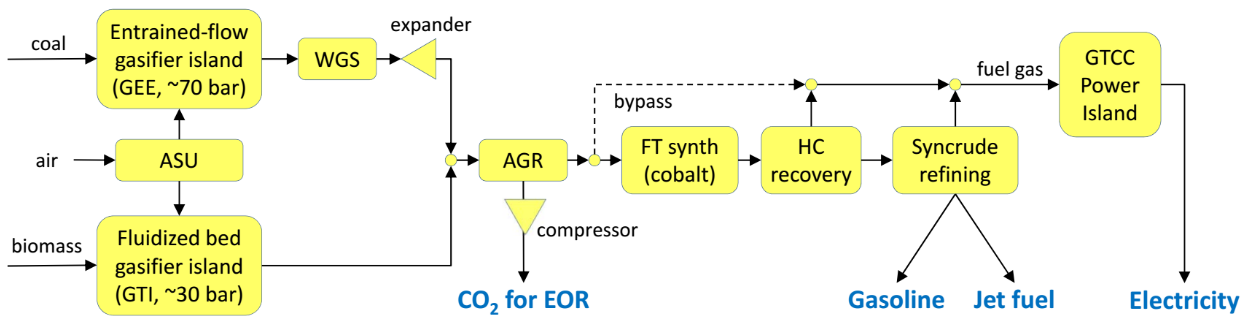

Figure 8: Block flow diagram of one potential coal-and-biomass-to-liquids (CBTL) plant. Source: (Larson, Liu, Li, Williams, & Wallace, 2013)

Biomass can be converted to fuels using heat and chemical-based approaches. Non-food/lignocellulosic feedstocks are dried, ground, and converted to a gas using oxygen and/or steam. Biomass can represent the sole source of carbon for the fuel synthesis, or it may be gasified in a plant along with conventional fossil fuels such as coal or petroleum coke. The product gas from the gasifiers is cooled and cleaned and can be used to produce fuels and chemicals such as hydrogen, substitute natural gas (SNG) via methanation, diesel, gasoline, jet fuel through Fischer-Tropsch (F-T) and refining steps, and methanol, which can be further processed to dimethyl ether, gasoline, plastics, and formaldehyde. The biomass synthesis gas does not have enough hydrogen molecules to produce chemicals and needs to be "shifted" or further processed. The proportion of hydrogen to carbon monoxide in the gas is adjusted using the water-gas shift reaction, which produces CO_2 and H_2 from CO and H_2O. The CO_2 is separated from the shifted synthesis gas using pre-combustion CO_2 capture technologies such as physical solvent absorption (Selexol, Rectisol).

CO_2 capture from biomass-based F-T fuel production is required as a part of the synthesis process. Process CO_2 emissions vary from 4.4 to 4.9 kg CO_2 per kg of F-T product (~0.59 t-CO_2/bbl F-T product) (Carbo, Smit, & van der Drift, 2010; NETL, 2013). A 100% biomass-fed F-T facility with a capacity of 10,000 bbl/d (1192 t F-T products/d) could capture up to 2 million t/y (Carbo, Smit, & van der Drift, 2010).

Conventional crude-based jet fuel life cycle GHG emissions amount to 87.4 g-CO_2e/MJ (LHV basis) (Skone, 2011). Coal-based jet fuel produced under conditions when the captured CO_2 is used for EOR has life cycle GHG emissions of ~92 g-CO_2e/MJ. CBTL jet fuel configurations with 31% switchgrass (thermal input) result in 15 to 28% reductions in life cycle CO_2 equivalent emissions when compared to petroleum jet fuel, but net emissions depend on whether the CO_2 is used for EOR or stored in saline aquifers. Larger extent of life cycle GHG emission reductions (over 50% compared to baseline jet fuel emissions) can be obtained by natural gas-biomass-to-liquids (GBTL) configurations both without (65% biomass, 35% natural gas) and with (30% biomass) CO_2 capture (Haq & Gupte, 2014).

4.3 Industrial sources

4.3.1 Pulp and paper

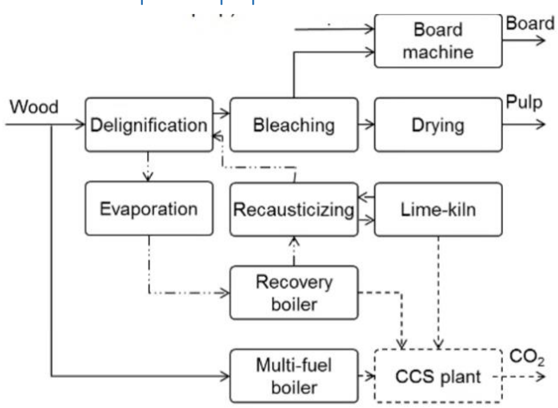

Figure 9: Block flow diagram of CO2 capture applied to the pulp and paper manufacturing process (IEAGHG, 2016).

Integrated paper-and-pulp facility produces paper as the primary product. Pulp and paper production (Figure 139) consists of preparing the wood, separating the cellulosic fibers in the wood from the wood matrix (pulping) using mechanical and/or chemical means, washing the pulp and recovering chemicals for the pulping process, pulp screening, bleaching and treating the pulp to form paper (papermaking). There are three main chemical pulping processes – kraft, soda, and sulfite pulping, which use different reagents to remove cellulose fibers from the wood matrix.

Of these, kraft pulping is the most common process used for virgin (i.e., not previously used) fiber. Liquor (pulping reagent) preparation and recovery represents a major source of CO_2 emissions in pulp and paper making. It consists of black liquor concentration, combustion of the black liquor, and causticizing and calcining steps.

Black liquor concentration: The dilute (12-15% solids) weak black liquor (consisting of wood lignin, organic materials, oxidized inorganic compounds, sodium sulfate Na_2SO_4, sodium carbonate Na_2CO_3) is concentrated using a series of multiple-effect evaporators (MEEs) to increase the content of the solids to 50% (EPA, 2010). This step helps to improve the heating value of the liquor when it is burned in a recovery furnace to produce steam.

Recovery furnace: Organic components in the black liquor are burnt in the recovery furnace and the inorganic chemicals are recovered in a molten state. The steam generated in the furnace is used for cooking wood chips, concentrating black liquor, preheating air, and drying pulp and paper. The process steam is supplemented by burning wood or coal in power boilers.

Causticization and calcining: The smelt from the recovery furnace is dissolved to form the green liquor (primarily Na_2S and Na_2CO_3, with insoluble unburned carbon, inorganic impurities), which is clarified and causticized (i.e., Na_2CO_3 is converted to NaOH forming $CaCO_3$) using slaked lime $Ca(OH)_2$ to produce white liquor for the pulping process. Lime mud collected from the white liquor clarifier is burnt in a lime kiln to regenerate lime for the caustization process.

Biogenic CO_2 capture from pulp and paper making: Unlike the cement industry, most of the CO_2 emissions in pulp and paper production is biogenic (i.e., CO_2 emitted by the combustion of plant material) (Kangas, 2016). For example, the biogenic CO_2 emissions from a standalone kraft pulp mill would be roughly 23 times the emissions from fossil fuels used in the kiln or for supplemental firing (2.59 tonne per tonne of air-dry ton of pulp [t CO_2/adt], vs. 0.11 t CO_2/adt) (IEAGHG, 2016). For a typical pulp mill, roughly half of the incoming wood is converted to fiber (i.e., paper products) and tall oil. The other half is eventually burnt in the boiler, resulting in biogenic CO_2 emissions. Recovery boilers represent the biggest source of CO_2 in the pulp and paper industry (Kangas, 2016). The quantity of biogenic CO_2 emissions from the recovery boiler are 3.8 times the emissions from the multi-fuel boiler and the lime kiln (IEAGHG, 2016). Standalone kraft mills or integrated pulp and board mills produce excess steam and power and between 666-1127 kWh of electricity can be exported from a typical pulp and board mill and kraft pulp mill per air-dry ton of pulp respectively (Kangas, 2016). The flue gas streams from the recovery boiler, calciner, and black liquor concentration can be fed to a carbon capture system, removing the CO_2. Amine solvent CO_2 capture and compression consumes electricity and steam, and CO_2 capture from the pulp mill alone requires additional steam to be extracted from the steam turbines to supply the CO_2 reboiler load. Because it requires additional power compared to the pulp making process, paper or board making would lower the amount of electricity exported from integrated mills compared to standalone pulp mills. Therefore, capturing CO_2 from an integrated pulp and paper/board mill would require an auxiliary boiler to supply the steam required for solvent regeneration. Starting in 2018, CO_2 Solutions Inc. will capture up to 30 t CO_2/d from a softwood kraft pulp mill in Quebec, Canada. The captured CO_2 will be transported and used at a vegetable greenhouse (Healy, 2016). BECCS for pulp and papermaking can result in negative CO_2 emissions of the order of 2.3 t CO_2/air-dried tonne [adt] pulp (IEAGHG, 2016).

4.3.2 Waste Incineration

The composition of solid waste varies geographically. It can include food waste, garden (yard) and park waste, paper and cardboard, wood, textiles, diapers, rubber and leather, plastics, metal, and glass wastes. It includes the wastes collected and treated by municipalities but may or may not include wastes sludge), from municipal sewage sludge), municipal construction and demolition (World Bank, 2012). The energy generated by burning municipal solid waste (MSW) depends on the ratio of the biogenic to non-biogenic components of the waste stream. Typically, combustible non-biogenic materials (e.g., plastics) have higher heat content. The biogenic component of MSW is higher on a volume-basis (e.g., 63% of the U.S. MSW in 2014 (EPA, 2016)), however, because its energy content is around three-fifths of the non-biogenic (e.g., plastics) fraction, biogenic MSW contributes 51% of the energy generated in U.S. waste-to-energy (WtE) plants (EIA, 2014). The approximate energy content of MSW combusted for energy recovery ranges from 10 to 12 MJ/kg (Themelis & Mussche, 2014). WtE plants recover part of this energy as steam and/or electricity. Incineration or gasification of the MSW also reduces its volume and reduces the emissions that would be emitted if the waste was landfilled. WtE is of particular interest in countries with growing population, decreasing availability of landfills, or high landfill tipping fees. The percent of total MSW that is burnt for energy recovery varies significantly across the world, from 70% in Japan, 53% in Norway, 26% in UK, to 13% in the United States (EIA, 2014). 74 WtE facilities in the United States with a combined heat and power capacity of 2,769 MW processed ~26 Mt/y of MSW in 2014, and generated ~14TWh of electricity (536 kWh_e/t MSW). In the United States, ~1 kg of biogenic CO_2 and 0.7 kg non-biogenic (fossil) CO_2 emissions are emitted per kWh of electricity generated from WtE plants in 2014 (EIA, 2014; EPA 2014].[3] According to the Confederation of European Waste-to-Energy Plants (CEWEP), 88.4 Mt of waste were thermally treated in Europe in 2014 in 455 plants, generating 38 TWh of electricity and 88 TWh of heat, and corresponding to an equal amount of CO_2 emissions being emitted to the atmosphere (approximately 64.6 Mt CO_2; IPCC, 2011).[4] The amount of waste being landfilled in the EU varies widely. In 2014, only 6.5% (88.4 Mt) of the waste treated in EU was incinerated and more than two-fifths (43.6%, or 593 Mt) of the waste was landfilled. If a considerable portion of the landfilled waste (593 Mt) was used for WtE, it could result in additional electricity and heat generation which could expand the market for CO_2 capture from waste incineration. There is, therefore, a large potential for applying CCUS to both retrofit and greenfield commercial projects for the WtE sector within the short term. Globally, over 1600 WtE plants, with an installed electric generating capacity of 11,311 MW converted 228 Mt/y MSW (WTERT, 2013). Therefore, the global potential is much larger, particularly in populated countries with high growth rate. For example, China had 223 WtE plants at the end of 2015, and plans to double that number in the next three years, increasing the amount of waste burned by 2.5 times to 500,000 tonnes per day by 2020 (Stanway, 2016). This scenario would lead to an estimated emission of 166 Mt CO_2 (biogenic and fossil-based) from WtE plants in China every year.

Currently, there are two pilot-scale demos of CO_2 capture from waste incineration power plants. The emissions reduction technologies that would be normally installed on a WtE power plant may be sufficient to clean up the flue gas prior to CO_2 capture. However, data from large scale tests is needed to confirm this. In 2013, Toshiba installed an amine CO_2 capture system at the Saga MSW incineration plant in Japan. The MSW incineration plant handles 220 t/d waste, of which 70% is derived from biomass. CO_2 emissions (without capture) from the power plant are 220 t-CO_2/d. In 2016, the company started selling the captured CO_2 (10 t-CO_2/d) from the incinerator flue gas and supply the CO_2 for crop cultivation and algae culture (Toshiba, 2016). The captured CO_2 is transported in the gas phase via a 200 meter pipeline to a 2 hectare algae cultivation facility producing astaxanthin, a fine chemical used in cosmetics and as a nutritional supplement (Tanaka, 2016). Aker Solutions' solvent CO_2 capture technology is being tested at a WtE plant in Klemetsrud, Norway at the pilot scale. 60 percent of the

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[33] Note that neither the EPA nor the IPCC enumerate biogenic CO_2 emissions in plant-, or country-level total estimates. The biogenic emissions were obtained from the GHG reporting program data for the WtE facilities with CO_2 emissions exceeding 25,000 t/y. Only considering reported estimates of kg-CO_2 would lead to erroneous results as they might not account for the biogenic CO_2 emissions from the combustion of biological components of MSW.

[4] The IPCC and other reporting frameworks do not account for biomass CO_2 emissions, only fossil CO_2 emissions. Biomass emissions are considered neutral, which is sufficient from a reporting perspective, but accurate biomass CO_2 inventory is nevertheless important when designing a CO_2 capture system – these emissions would also need to be captured. This is the main drawback in applying CO_2 emission factors from reporting frameworks such as the IPCC to MSW incineration (or related technologies). The actual CO_2 emissions end up being underestimated.

waste material handled at Klemetsrud is biogenic waste (Engen, 2016). The flue gas contains around 10% CO_2 and (Harvey, 2016). The WtE plant at Klemetsrud emits ~0.3 Mt-CO_2/y. Amine and oxy-combustion options for capturing CO_2 from WtE plants are further discussed by Helsing (2015).

4.3.3 Cement

Modern cement production process

Modern Portland cement production involves countercurrent heating of the limestone raw meal in cyclone preheaters, a fired pre-calciner, and a fired rotary kiln. Lime formed by the calcination of limestone reacts with silica (SiO_2) and alumina (Al_2O_3) forming calcium aluminosilicates (clinker). Clinker produced in the kiln is cooled by air and is stored before being milled to fine particle sizes in cement mills where other additives such as fly ash can also be added.

Bio-derived fuels in cement production and CO_2 capture: CO_2 in cement plants is emitted both from limestone calcination and from fuel combustion (e.g., coal, biomass, rubber tires) to supply the heat for the endothermic calcination reaction. Members of the World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative pledged to reduce CO_2 emissions by 20-25% by 2030 - a reduction of 1 Gt versus the business as usual scenario (Guenioui, 2015). The Cement Action Plan is part of WBCSD's Low Carbon Technology Partnerships initiative (LCTPi) and includes scaling up the use of alternative fuels and raw materials (AFR) in the cement-making process. The use of alternative fuels and refuse in cement production and downstream CO_2 capture and storage reduces the emissions from cement plants and reduces any emissions that would have been emitted from solid waste incinerators or landfills (WBCSD, 2016). CO_2 in cement production is mostly generated in the calciner and the kiln.

Biomass is one category of AFR that can be used in a cement plant instead of conventional fuels. The type and quantity of bio-derived fuels which are typically co-fired with coal in the kiln varies geographically and include olive waste, wood chips, sugar cane refuse, and refuse-derived fuels such as Subcoal®. Agricultural, organic, diaper waste, and charcoal represents almost 30% of the biomass used globally for cement production, followed by wood and non-impregnated saw dust (14%), animal meal (13%), and dried sewage sludge (~8%) [The rest of the biomass used in cement production does not have a specific category (34%)] (WBCSD, 2014). The use of biomass is challenging because of the lower energy content of the unprocessed biomass (e.g., raw wood has 30% the calorific value of coal), and because of the high initial moisture content, which would create large amounts of steam, leading to reduction in kiln (clinker) throughput due to the higher volume of combustion products generated per unit of clinker. Furthermore, the lower energy content and higher moisture content can lead to reduced flame temperatures and longer flame in the kiln, adversely impacting clinker reactivity (De Raedt, Kline, & Kline, 2015). AFRs vary in homogeneity, energy content, and particle sizes. Typically, high-energy content, homogenous material of less than 30 mm is required for the main burner (kiln), whereas the preheater calciners can handle particle sizes up to 80 mm (Streinik, 2016). Further, the main burner-grade solid-recovered fuel (SRF) typically has a higher energy content (19 to 22 GJ/t fuel) compared to calciner-grade SRF (16 to 19 GJ/t) (Roberts & Jennissen, 2015). Compared to biomass or MSW incineration, the high temperatures and longer residence time of cement kilns allows for a more complete combustion of fuel, thus reducing air emissions. Unlike incineration, the cement manufacturing process produces limited residual waste, as nearly all non-combusted material is incorporated into the clinker (The Pembina Institute and Environmental Defence, 2014).

CO_2 emissions from fuels depend on the CO_2 intensity of the fuel (amount of CO_2 per unit energy content of fuel) and the amount of thermal energy required for a unit of cement or clinker. In 2014, the weighted-average thermal energy consumed in global cement production was 3500 MJ/t clinker (grey clinker). The amount of biomass co-fired in cement plants (~6% of total thermal input) is small when compared to quantities of fossil fuels (~84%) and fossil and mixed waste (~10%) used (WBCSD, 2014). On the other hand, industry data also show that the fraction of thermal energy supplied by biomass grew almost seven times, from 2000 to 2014, which indicates increasing world-wide adoption of biomass as a fuel in cement production. The carbon intensity of the fuel mix has decreased from 89.6 g-CO_2/MJ (for producing grey clinker) in 2000 to 85.8 g-CO_2/MJ in 2014 (WBCSD, 2014).[5] Increased use of biomass in cement plants would further lower the carbon intensity because biomass CO_2 emissions are considered neutral under the IPCC and CO_2 and energy accounting reporting standards for the cement industry (WBCSD, 2011). The fuel-CO_2 emissions (accounting for fossil waste and fossil fuels) for cement production would be roughly 300 kg-CO_2/t clinker, which is 36% of the gross CO_2 emissions (842 kg-CO_2/t clinker). Increasing the biomass used in cement from the global average of 6% to 15% would increase the amount of CO_2 emitted per unit of clinker (while reducing the 'reported' CO_2 emissions, which considers biomass emissions to be neutral) from ~305 kg-CO_2/t clinker to 313 kg-CO_2/t clinker.[6] Therefore, the CO_2 capture unit would need to capture slightly larger quantity of CO_2 with increasing biomass co-firing.

CO_2 capture from cement plans with biomass co-firing would be largely similar to the case without biomass co-firing. Post-combustion CO_2 capture technologies can be retrofitted to existing cement plants to capture CO_2 in the flue gas exiting the stack. Because there is no large steam boiler on-site, a separate steam boiler is needed if using steam to strip CO_2 from adsorbents or absorbents. Amines can be used for capturing CO_2 from cement plants, however, FGD and SCR units are needed upstream of the CO_2 capture process. Furthermore, the oxygen content of cement plant stack gas at the exit of the preheater cyclone strings is approximately 2-5% (dry basis) and 7-12% in the stack (ECRA, 2009). Only solvents and sorbents tolerant to oxidative degradation at high temperatures in the CO_2 stripper or membranes systems are recommended.

Four CO_2 capture technologies (amine, solid sorbent, membrane, and regenerative calcium cycle) were tested using real flue gas at the Norcem cement plant in Brevik, Norway (Bjerge & Brevik, 2014), with a goal of evaluating technologies for capturing 400,000 t CO_2/y (around 50% of the plant's total CO_2 emissions). NO_x and SO_x in the cement flue gas at Norcem's Brevik plant are removed before CO_2

[5] The CO_2 intensity of solid biomass is higher than that from fossil fuels. The IPCC default emission factor for solid biomass is 110 g-CO_2/MJ. Wood waste has an emission factor of 112 g-CO_2/MJ, and the biomass fraction of MSW has an emission factor of 100 g-CO_2/MJ (on a lower heating value basis). CO_2 from biomass is not accounted for in typical protocols and standards, but the quantities are relevant when designing a CO_2 capture and storage/utilization system to handle the CO_2. [http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf]

[6] This assumes 110 g-CO_2/MJ for solid biomass and 85.8 g-CO_2/MJ for fossil waste and fossil fuels.

removal. By 2030, Norcem plans to achieve zero-life cycle CO_2 emissions from its concrete products through a combination of CCUS and the use of biomass energy for cement production (around 30% of the fuel used at Norcem is derived from biomass) (Bergsli, 2017). CO_2 capture at the Norcem cement plant is one of the three industrial CCUS projects selected by Norway for detailed concept/front end engineering and design (FEED) studies.

4.4 Summary of Economic Analyses

Co-firing: The total installed costs of biomass power generation and co-firing technologies varies significantly by technology, feedstock price, location, and country. As such, costs for co-firing biomass at low levels have also been reported in the range of $400-600/kW with investment costs ranging between $140-850/kW (IRENA, 2012).

In 2014, 487 billion kWh of electricity was produced worldwide from waste and biomass, nearly 40% in the EU-27 countries (EIA, 2016). This represents an opportunity to deploy BECCS technologies in the EU-27 countries. Retrofitting existing pulverized coal power plants to co-fire biomass increases both capital (additional equipment needed for handling biomass) and operational (e.g., biomass fuel) costs. The co-firing of 10% biomass (by heat content) in a 550 MW power plant is estimated to increase the cost of electricity by 31% for hybrid poplar co-firing, and 14% for co-firing forest residues (Skone & James, 2012). The operating and maintenance (O&M) cost of fuel is the biggest contributor to the increase in the cost of electricity, based on a cost of $1.64/GJ (Illinois No. 6 bituminous coal, 2007$) and hybrid poplar cost of $4.27/GJ and forest residue cost of $1.73/GJ (Skone & James, 2012). The ratio of the costs of coal and forest residue (0.95) compares well with the ratio of average price of coal to the price of wood and waste for electric power generation (~0.88 in 2014, 1.05 in 2013) in the United States (EIA data). The additional capital expenditure required for the biomass co-firing was estimated to be $230/kW (2007$).

Fischer-Tropsch fuels: CBTL configurations with CO_2 capture require the selling price (RSP) of the F-T products (e.g., jet fuel) to be more than the spot price of conventional jet fuel (DOE/NETL-2012/1563; DOE/NETL-2015/1684)[7]. For example, the average RSP for jet fuel from a CBTL plant fueled by Montana Rosebud sub-bituminous coal and southern pine biomass (11.7% heat input) was estimated to be $138/bbl compared to $98/bbl for conventional jet fuel and $135/bbl for a CTL (0% biomass) configuration (Skone, Marriott, Shih, & Cooney, 2012). Higher levels of biomass input further increase the product cost. The use of torrefied biomass lowered the RSP, whereas gasifying the biomass in a separate gasifier increased the RSP.

Ethanol: The cost of capturing CO_2 from the ethanol fermentation step is low because the gas stream consists of just CO and moisture and needs to be only dried and compressed. The range of estimated costs of capturing and compressing CO_2 emissions from the ethanol fermentation process is 10/t CO_2 to

[7] RSP is the minimum price at which the products need to be sold to recover the annual revenue requirement of the plant, which includes the operating costs, debt service (interest), and revenue to provide the expected rate of return for the investors. It is assumed that 50% of the project capital costs were financed by debt service at an interest rate of 8%. The internal rate of return on equity was assumed to be 20% in the DOE/NETL-2012/1563 report.

\$22/t CO_2 depending on the relative size of the ethanol facility and associated capital and operating expenses. These estimates do not include the costs of transportation and storage. (IEAGHG, 2011).

Pulp and paper: Biogenic CO_2 emissions are considered neutral under the EU's emissions trading system (ETS). Industrial facilities emitting biogenic CO_2 are not required to purchase CO_2 credits to offset their biogenic CO_2 emissions. On the flip side, EU facilities also do not receive preferential credits for capturing the biogenic CO_2. Studies indicate that the cost of avoiding CO_2 emissions from a kraft pulp mill would be around \$56 to \$84/metric tonne of CO_2 respectively (IEAGHG, 2016). For an integrated kraft pulp and board mill, the avoided CO_2 emission costs for capture would be \$75 to \$85/t CO_2 respectively (IEAGHG, 2016). These are significant costs, because the break-even cost of pulp production is increased by around 30% in the case of capturing 90% of CO_2 emissions from a standalone kraft pulp mill.

Cement: From a plant operator's perspective, the use of biomass in cement plants is affected by market conditions. When there is abundant supply of cement, a plant can afford to lose some production to minimize energy costs. However, when the market is sold-out, any loss in clinker output would negatively impact the plant profitability, negating the advantage of using alternative fuels with higher moisture and lower energy content (Abbas & Jun, 2015). For cement plants already co-firing biomass, the costs of installing a CO_2 capture system would be mostly similar to cases without biomass co-firing. The cost of retrofitting a cement plant in Norway with amine-based post-combustion CO_2 capture was estimated to be around \$51/t CO_2 (Barker, 2013).

Waste incineration: Waste can either be landfilled or incinerated. In countries with low landfill tipping fees, it would not be feasible to add the costs of CO_2 capture to an already expensive WtE plant without receiving some credits or revenues from the captured CO_2. Tang, Ma, Lai, and Chen (2013) showed by LCA of MSW combustion scenarios in China that oxy-fuel capture has both better efficiency and environmental impacts than MEA-based post-combustion capture. Klein, Zhang, and Themelis estimated the costs of oxycombustion-based CO_2 capture on a WtE plant, and found that the breakeven landfill tipping fee for the project to be feasible was around \$59/ton of MSW.

An overview of this section is provided in Table 5.

Table 5: Summary of costs of technologies considered in this report

Technology	Type	Capital cost	CO_2 partial pressure in the inlet gas, kPa	CO_2 capture cost	Other
Biomass co-firing	Retrofit	$140-$850/kW	10-15		
Fischer-Tropsch fuels	CBTL plant, sub-bituminous coal + southern pine (11.7%)		460-500		RSP of fuel: $138/bbl vs. $98/bbl for jet fuel
Ethanol	Fermentation CO_2 emissions		~95	$5-$10/t to $22/t	
Pulp and paper	Amine CO_2 separation		10-15		Avoided cost: $70-$72/t for pulp mill
Cement			14-21	$51/t	
Waste incineration			10-15		Breakeven tipping fee for oxycombustion CCS: $59/t-MSW, or ~$ 65/t-CO_2

4.5 Summary of Technical Challenges and R&D Opportunities

The technical challenges are summarized below.

Table 6: Technical Challenges

Challenge	Co-firing	F-T fuels	Ethanol	Pulp and paper	Cement	Waste incineration
Can steam from process supply all/part of steam required (for CO_2 capture)?	Yes	Yes	NA	Yes	Yes	Yes
Is flue gas pretreatment required (before CO_2 capture)?	Yes	Yes	No, minimal gas scrubbing	Yes	Yes	Yes
Can a large part of captured CO_2 be biogenic?	Yes, varies with amount of biomass	No, 10-15%	Yes	Yes	No	Yes, varies with MSW (50-60%)
Energy requirement for CCS	Moderate	Low	Minimal	Moderate	Moderate	Moderate

R&D Opportunities

There is a need for establishing research programs exploring BECCS concepts in several sectors. Unlike the power sector, there are no well-defined research programs that outline a way to achieve the commercial deployment of BECCS for most of the industries discussed in this report by successive RD&D efforts at several scales. Current RD&D projects for specific industries were discussed previously in this section. Some of the common research issues to be addressed include:

- Evaluating the impact of CO_2 capture on plant operations and competitiveness: The capture of CO_2 from ethanol plants is less energy intensive than capturing CO_2 from cement or pulp/paper mill flue gases. Systematic evaluation of the impacts on production and operational costs is needed.
- Studying the impact of gas stream impurities on CO_2 capture technologies that were developed for the power generation industries: The types and composition of impurities in gas streams from biomass co-firing, ethanol, biomass-to-liquids plants, cement, and waste incineration plants is different from those encountered in gas streams in power plants. For instance, waste incineration plant flue gas may require pretreatment to remove chlorine, dioxins and other compounds before the CO_2 separation step.
- Exploring novel means to recover waste heat from industrial processes and integrate this with the CO_2 capture and compression step: Part of the steam required for CO_2 capture from paper and pulp and cement gas streams can be recovered from flue gas waste heat. Studies on the heat/process integration between the CO_2 capture process and the production plant are needed to gauge what level would be most optimal.
- Exploring the diverse incentives and opportunities that drive the adoption of BECCS: With the exception of pulp and paper, most other processes (co-firing, XTL, ethanol, cement, WtE) are driven by incentives and regulations such as renewable energy portfolio standards, industry GHG standards, high waste disposal fees, and production and/or investment tax credits. These factors determine the economic feasibility of the capturing and storing biomass-derived CO_2.

5 Findings and Recommendations

The following section provides a summary of the findings that are highlighted in recent sections of this document, and the recommendations for further work in the area of BECCS development and deployment.

5.1 Report Summary Findings

A summary of the primary findings described in the Technical Summary of Bioenergy Carbon Capture and Storage that are provided by the Technical Group Task Force are as follows:

Challenges and Benefits of BECCS

- BECCS development and implementation in both the power generation and industrial sectors faces some of the same challenges and hurdles that must be addressed in plants which burn coal, gas, and oil. That is, the high capital cost and energy penalty associated with CCUS results in an unfavorable economic condition for the deployment of new BECCS projects without the intervention of government in the form of subsidies and regulations.
- When considering the application of BECCS in bioenergy, sustainability of available feedstocks and efficiency of the whole bioenergy conversion system remain to be issues that must be addressed.

Biomass and Carbon Storage Resource Assessment

- Biomass accounts for 10% of global primary energy used for heat and electricity (IEA, 2017) and is also utilized for industrial processes. The United States leads the world in biomass-generated electricity, followed by Germany and China (IEA, 2015).
- Some of the important factors that will affect bioenergy sustainability include: impact on soil quality, biomass quality, harvest levels, water use and efficiency, water quality, social impacts including allocation for land for bioenergy crops, price and supply of other commodities, and biological diversity in the landscape where bioenergy production is proposed.
- For biomass conversion and wide-scale deployment of bioenergy to reduce GHG emissions or achieve negative emissions, the processes must be integrated with CCUS (IEAGHG, 2014).

Direct and Indirect GHG emissions

- GHG can be in the form of direct and indirect emissions. Reaching global emissions targets set forth during COP21 will require bringing annual global emissions below 20 Gt CO_2-eq/year and mitigating upwards of 600 Gt of CO_2 over the 20th century. BECCS has the potential to mitigate up to 3.3 GtC per year (Smith, 2016).
- Deployment of BECCS as a climate mitigation solution will necessitate planting bioenergy crops on approximately 430-580 million hectares of land (approximately one-third of the arable land on the planet or about half of the U.S. land area (Williamson, 2016).

Life Cycle Assessments

- Comparing various combustion options, including co-firing and dedicated biomass combustion, the net life cycle CO_2 emissions appear to depend on biomass type and the combustion method (Weisser, 2007; Odeh & Cockrell, 2007; Cai, et al., 2014; Schakel et al., 2014).
- The net life cycle CO_2 emissions also depend on the data, LCA methodology, and analysis assumptions and in many cases, the data and assumptions are inaccurate or out of date (Schakel et al., 2014).
- The lowest net life cycle CO_2 emissions involve the use of poplar biomass using Biofuel IGCC technology with co-firing percentage of 100% (See Schakel, Meerman, Talaei, Ramirezrez, & Faaij, 2014 for Study references).

Commercial Status of BECCS Technology Development

- The majority of BECCS projects are located at ethanol fermentation facilities.
- The Illinois Basin Decatur and now the Illinois Industrial CCS Project (IL_ICCS) Archer Daniel Midland (ADM) ethanol plant is now capturing a total of 1 $MtCO_2$/yr and is the largest operational BECCS project in the world.
- There are currently five additional BECCS projects in operation, which capture approximately 0.85 $MtCO_2$/yr. Conestoga's Arkalon and Bonanza ethanol plants, RCI/OCAP plant in Rotterdam, NL on Shell's Pernis refinery and Abengoa's ethanol plant, Maasvlatke power plant, Huskey energy's ethanol plant, Saga City waste to energy plant. Significantly more CCUS projects will be necessary to achieve the required CO_2 emission reductions.

Government Programs

- Government support for BECCS projects is extremely important in the future deployment of these projects. In the United States, the US Department of Energy has provided a portion of the funding for the ADM BECCS project to support construction and operation of the facility.
- Another important government program in the United States that would support BECCS is the an expansion of the section 45Q in the U.S. tax code which increases tax credits to $50/t$CO_2$ and saline storage and $35/t$CO_2$ for utilization. These could lead to increased ethanol BECCS projects for both saline storage and associated storage during EOR, respectively (NEORI, 2016)
- The California Air Resource Board (ARB) is in the process of determining how CCUS can contribute towards the state's cap-and-trade and low carbon fuel standard regulations, both of which could drive BECCS projects by providing a framework to account for stored CO_2 to reduce the carbon footprint of low carbon transportation fuels sold into the California market (CEPA, 2016).
- Language in the U.S Senate version of the Energy Bill introduced in 2016 authorized $22M/yr for 5 years to support a partial BECCS co-fired biomass + coal power project in the southeastern United States (CCR, 2016), and the U.S. Department of Energy's Advanced Projects Research Agency-Energy (ARPA-E) has also explored launching a program dedicated to BECCS innovation in the near future (Stark, 2016). Bio-CCS research has been funded through the EU Framework Programme for research and Innovation's Horizon 2020 Program since 2014.
- In Norway, the Klemetsrud partial-BECCS facility at a municipal solid waste plant is receiving support from the City of Oslo government (Engen, 2016) and the Ministry of Petroleum and Energy through the CLIMIT program.

Market Drivers for BECCS Deployments

- The most significant driver for BECCS projects today is policy support.
- In the United States, EOR can help drive some of the demand for ethanol BECCS projects if either co-located near existing oil fields or CO_2 pipeline. Regional clusters of bioenergy plants such as in the Midwest United States would benefit from a dedicated CO_2 pipeline gathering systems to transport CO_2 to EOR markets.
- Corporate demand for BECCS projects is very low. The biggest potential hurdle with BECCS projects for corporate buyers is on the GHG accounting side. Corporations are exposed to potential negative public perception of BECCS as an effective climate strategy.
- Finance is an important factor for BECCS projects. The cost of capital is high for early generation BECCS projects. Programs such as loan guarantees, extending master limited partnership tax structures for BECCS projects, and offering government-backed price-stabilization contracts for CO_2 off-take can enable faster and wider market adoption of BECCS projects.

Barriers to Large scale BECCS Demonstration and Deployment

Technical

- There are many barriers to large-scale BECCS deployment which the industry will need to address prior to wide scale adoption of the technology.

- Technical barriers are related to the biomass combustion/conversion process which can lead to slagging, increased corrosion, and fouling (Pourkashanian. et al., 2016).
- Further research is needed to identify feedstocks that require limited processing, compatibility with existing boiler and pollution control equipment, and reduction in cost of processing equipment costs and associated energy costs.

Economics and incentives

- There is no incentive for CCUS or even BECCS, besides limited government support.
- A BECCS plant in the power sector might provide a double benefit: producing low-carbon electricity and negative emissions at the same time (Dooley, 2012).
- Co-firing biomass in heat and power plant appears to be the most efficient way in terms of GHG reduction targets in a cost-effective manner (REN21 2013; Junginger, et al., 2014; Sterner and Fritsche, 2011).
- Many low-carbon policies and GHG accounting frameworks do not appropriately recognise, attribute, and reward BECCS and negative emissions in general, especially regional cap-and-trade schemes (IEAGHG, 2014; Zakkour, et al., 2014). As a result, there are no incentives to capture and store biogenic emissions over zero emissions, e.g., from dedicated biomass firing without CO_2 storage.
- Public perception of BECCS is composed of two parts: 1) image of biomass/bioenergy and 2) CCUS. Public perception of BECCS varies with location and social/cultural background and it can be either a driver or a barrier. BECCS generally has a lower profile than fossil-CCUS and appears to lack support among external, as well as its own, stakeholders (Dowd, et al., 2015). When competing with other mitigation options, such as renewable energy and energy efficiency, fossil-CCUS and BECCS are usually perceived as non-favourable (TNS 2003).

Land Demand and Land Use Change (LUC: dLUC and iLUC)

- A critical issue related to sustainable bioenergy production for BECCS is LUC. LUC can be direct or indirect. The balance between LUC and association emissions is critical as it may render any zero emissions, negative emissions, or double benefit assumption invalid (Kemper 2015).
- Lack of infrastructure (i.e., for biomass, natural gas, and CO_2 as well as CO_2 storage/utilization) could be a showstopper for BECCS projects. The timeline for CCUS deployment could be the most important cost barrier for BECCS (Edenhofer, et al., 2010; Tavoni, et al., 2012; Krey, et al., 2014; Kriegler, et al., 2014; Riahi, et al., 2014). Large-scale biomass supply chains and trade need further development. One issue of great concern is how to avoid food price increases due to land use competition. Improvements in crop yield increases, food waste reduction, and demand side changes could help free land for bioenergy production (Thomson, et al., 2010).

Water Usage

- Bioenergy applications require disproportionately high amounts of water, especially when compared to other energy production options (WEC, 2010). Irrigation of bioenergy crops is likely to be very costly and to compete with other uses. Research into high energy yield crops with reduced water demand are required for wide-scale deployment.

BECCS Technology Options and Pathways

- The power generation sector, which is comprised of the electricity and heat production industry, is a large contributor to global CO_2 emissions and contributes approximately 25-35% of the global GHG emissions (IPCC, 2014).
- Biomass firing and co-firing can substantially reduce GHG emissions in the production of electrical power (IRENA, 2012). A BECCS power plant may utilize pre-combustion, post-combustion, or oxy-fuel technology in the capture of CO_2.
- Biomass has been successfully used to supplement pulverized coal in power generation. The biomass industry supplies about 52 GW of global power generation capacity, mostly using wood pellets, municipal solid waste, agricultural waste (Block, 2009).
- Wood pellets are the preferred source of biomass used for BECCS in power generation (WBDG, 2016). Other types of biomass have been used including straws, grasses, animal wastes, forestry residues, and other agricultural processing residues (IEA, 2016).
- Typical biomass power plant sizes are based upon availability of local feedstocks and range between 10 and 50 MWe in size (IEA, 2012). The power generation efficiencies of plants in the 10-50 MWe size without CCUS range between 10-33%, lower than plants that burn natural gas or coal (IEA, 2012).
- Biomass combustion produces acid gases such as SO_X, NO_X, and HCl, but at levels that are lower than those for most coals. Trace metals such as mercury are present in flue gas from biomass plants at levels dependent upon the type of biomass that is used.
- Mercury emissions from pulverized coal plants can be reduced when co-firing with biomass if halogens are present in the biomass. (Cao, et al., 2008).
- Biomass fuels such as poultry litter that could be used in co-firing, for example, can contain higher levels of lead, arsenic, copper, iron, zinc, and mercury and may require additional treatment when used as a biofuel in power generation applications (Ewall, 2007).

Biomass Co-firing

- The co-firing of biomass at pulverized coal power generation plants is well established and cost-effective (IEA, 2016). The use of biomass co-firing provides co-benefits in reducing flue gas cleaning as acid gases such as SO_x, HCl, and NO_X are typically reduced in the flue gas (IEA, 2016).
- Different approaches to co-firing of biomass at pulverized coal power plants that have been used at several locations in North America and Europe (IEA, 2016). Co-firing ratios of biomass to coal have ranged between 5-50% (IEA, 2016). Co-firing can occur by gasification of the biomass in a separate gasifier to form a gas which is combined with air and injected into the pulverized coal boiler for combustion (IEA, 2016).
- In Europe, electricity generation from biomass peaked between 2005-2006 due to government subsidies (IEA, 2016) and again between 2010-2012. But without subsidies, a sharp reduction in electrical generation with biomass can occur, as it did in the Netherlands (IEA, 2016).

Large Coal to Biomass Conversions and Biomass Combustion Power Plant Projects

- Several successful demonstrations of pulverized coal power generation plants involving conversion to 100% biomass plants (IEA, 2016). The Drax Power (Drax Group) plant in Yorkshire, UK, the Ironbridge Power Station located in Shropshire, England, the Tilbury power station near London, England, the Les Awirs plant and the Max Green plant with DONG Energy in Belgium were all high profile power projects that converted their fuel source to biomass (IEA, 2016). The fuel for this facility is sourced from southeast United States, demonstrating the challenges of regional fuel supply.

- In North America, Canada installed 61 bioenergy plants through 2016 with a total of 1,700 MWe generating capacity (IEA, 2016).
- The Ontario Power Generation (OPG) Atikokan Generating Station was converted from a pulverized coal plant and is now the largest power generation facility in North America using 100% biomass with generating capacity of 200 MWe.

Thermal Gasification

- Similar to coal, biomass can be utilized in a thermal gasification process in which solid feedstock is transformed into a combustible synthetic fuel gas containing hydrogen (IEA, 2012). New developments in biomass power generation include the biomass integrated gasification combined cycle (BIGCC) concept. The Vaskiluodon Voima Oy power generating plant in Finland is one of the largest bio-gasification plants (140 MWe) to produce a gas that is burned in the existing power plant pulverized coal boiler to reduce coal consumption by approximately one half (C Breitholtzs, 2011).
- Pyrolysis is a process in which the biomass is heated in the absence of oxygen (IEA, 2012). The products of pyrolysis are charcoal, liquid pyrolysis oil, and a product gas which can be used as fuel in heat and power generation plants. Further work to determine whether mixing of the pyrolysis oil with conventional crude oil in refineries is feasible (IEA, 2012).

Fuels and Chemicals Production

- Currently, there are over 60 bio-refinery projects around the world producing alcohols, hydrocarbons, and intermediate chemicals from biomass like 1,4-butanediol (BDO) (Warner, Schwab, & Bacovsky, 2016).
- Global demand for biofuels grew between 2010 and 2015 and is projected to further grow over the next two decades. Global demand for ethanol grew from 2011 to 2014 (BP, 2017). Ethanol and bio-butanol represent a significant part of that demand growth (BP, 2017). Fermentation from corn-ethanol plants represents the largest single-sector CO_2 source for the U.S. CO_2 market.
- Raw CO_2 from ethanol fermentation contains trace sulfur compounds and acetaldehyde that must be removed before the gas is supplied for CO_2 utilization or storage. CO_2 sourced from corn-ethanol plants can displace sources with higher emissions and/or capture costs (Mueller, 2017). There are around 210 ethanol plants in the United States that together emit an estimated 100,000 T CO_2/d (Wittig, 2016). Of these, CO_2 is stored in saline formations or used for EOR, resulting in associated storage, at three plants:
  1. The ADM Decatur plant currently injects CO_2 to a saline aquifer for storage,

2. The Bonanza BioEnergy CCUS EOR project in Garden City, Kansas (Conestoga Energy) project captures ~100,000 T/y for EOR.
3. Conestoga Energy Holdings' Arkalon ethanol plant near Liberal, Kansas produces ~269,000 T/y (14 MMCF/d) CO_2 for EOR (Texas, Oklahoma panhandles).

Synthesis Processes

- Biomass can be converted to fuels using heat and chemical-based approaches.
- Biomass can be used to produce fuels and chemicals such as hydrogen, substitute natural gas (SNG) via methanation, diesel, gasoline, jet fuel through F-T and refining steps, and methanol, which can be further processed to dimethyl ether, gasoline, plastics, and formaldehyde.
- The CO_2 is separated from the shifted synthesis gas using pre-combustion CO_2 capture technologies such as physical solvent absorption (Selexol, Rectisol).
- CO_2 capture from biomass-based F-T fuel production is required as a part of the synthesis process
- Coal-based jet fuel produced under conditions when the captured CO_2 is used for EOR has life cycle GHG emissions of ~92 g-CO_2e/MJ. CBTL jet fuel configurations with 31% switchgrass (thermal input) result in 15 to 28% reductions in life cycle CO_2 equivalent emissions when compared to petroleum jet fuel, but net emissions depend on whether the CO_2 is used for EOR or stored in saline aquifers (Skone, 2011).
- Larger extent of life cycle GHG emission reductions (over 50% compared to baseline jet fuel emissions) can be obtained by natural GBTL configurations both without (65% biomass, 35% natural gas) and with (30% biomass) CO_2 capture (Haq & Gupte, 2014).

Pulp and paper

- Liquor (pulping reagent) preparation and recovery represents a major source of CO_2 emissions in pulp and paper making. Most of the CO_2 emissions in pulp and paper production is biogenic (i.e., CO_2 emitted by the combustion of plant material) (Kangas, 2016). Recovery boilers represent the biggest source of CO_2 in the pulp and paper industry (Kangas, 2016). The flue gas streams from the recovery boiler, calciner, and black liquor concentration can be fed to an amine solvent-based CO_2 absorber to remove the CO_2. Capturing CO_2 from an integrated pulp and paper/board mill would require an auxiliary boiler to supply the steam required for solvent regeneration.

Waste Incineration

- The composition of solid waste varies geographically. It can include food waste, garden (yard) and park waste, paper and cardboard, wood, textiles, diapers, rubber and leather, plastics, metal, and glass wastes.
- The energy generated by burning MSW depends on the ratio of the biogenic to non-biogenic components of the waste stream. The approximate energy content of MSW combusted for energy recovery ranges from 10 to 12 MJ/kg (Themelis & Mussche, 2014). Waste to Energy (WtE) plants recover part of this energy as steam and/or electricity. Incineration or gasification

of the MSW also reduces its volume and reduces the emissions that would be emitted if the waste was landfilled.

- WtE is of particular interest in countries with growing population, decreasing availability of landfills, or high landfill tipping fees. The percent of total MSW that is burnt for energy recovery varies significantly across the world, from 70% in Japan, 53% in Norway, 26% in UK, to 13% in the United States (EIA, 2014).
- There are 74 WtE facilities in the United States with a combined heat and power capacity of 2,769 MW processed ~26 Mt/y of MSW in 2014, and generated ~14 TWh of electricity (536 kWh_e/t MSW). In the United States, ~1 kg of biogenic CO_2 and 0.7 kg non-biogenic (fossil) CO_2 emissions are emitted per kWh of electricity generated from WtE plants in 2014 (EIA 2014, EPA 2014].[8]
- According to the Confederation of European Waste-to-Energy Plants (CEWEP) 88.4 Mt of waste were thermally treated in Europe in 2014 in 455 plants, generating 38 TWh of electricity and 88 TWh of heat, and corresponding to an equal amount of CO_2 emissions being emitted to the atmosphere (IPCC, 2011). The amount of waste being landfilled in the EU varies widely. In 2014, only 6.5% (88.4 Mt) of the waste treated in the EU was incinerated and more than two-fifths (43.6%, or 593 Mt) of the waste was landfilled. If a considerable portion of the landfilled waste (593 Mt) was used for WtE, it could result in additional electricity and heat generation which could expand the market for CO_2 capture from waste incineration.
- There is a large potential for applying CCUS to both retrofit and greenfield commercial projects for the WtE sector within the short term. Globally, there are over 1600 WtE plants, with an installed electric generating capacity of 11,311 MW converted 228 Mt/y MSW (WTERT, 2013). The global potential is much larger, particularly in populated countries with high growth rate.
- Currently, there are two pilot-scale demos of CO_2 capture from waste incineration power plants.
- Aker Solutions' solvent CO_2 capture technology is being tested at a WtE plant in Klemetsrud, Norway at the pilot scale. 60% of the waste material handled at Klemetsrud is biogenic waste (Engen, 2016). The flue gas contains around 10% CO_2 and (Harvey, 2016). The WtE plant at Klemetsrud emits ~0.3 Mt-CO_2/y. Amine and oxy-combustion options for capturing CO_2 from WtE plants are further discussed by (Helsing, 2015)

Cement

- CO_2 in cement plants is emitted both from limestone calcination and from fuel combustion (e.g., coal, biomass, rubber tires) to supply the heat for the endothermic calcination reaction. CO_2 in cement production is mostly generated in the calciner and the kiln.
- Members of the WBCSD Cement Sustainability Initiative pledged to reduce CO_2 emissions by 20-25% by 2030 (Guenioui, 2015).

[88] Note that neither the EPA nor the IPCC enumerate biogenic CO_2 emissions in plant-, or country-level total estimates. The biogenic emissions were obtained from the GHG reporting program data for the WtE facilities with CO_2 emissions exceeding 25,000 t/y. Only considering reported estimates of kg-CO_2 would lead to erroneous results as they might not account for the biogenic CO_2 emissions from the combustion of biological components of MSW.

- The use of alternative fuels in cement production and downstream CO_2 capture and storage reduces the emissions from cement plants, as well as reduces any emissions that would have been emitted from solid waste incinerators or landfills (WBCSD, 2016). Biomass is one category of alternate fuels and raw materials (AFR) that can be used in a cement plant instead of conventional fuels.
- The lower energy content and higher moisture content can lead to reduced flame temperatures and longer flame in the kiln, adversely impacting clinker reactivity (De Raedt, Kline, & Kline, 2015).
- Compared to biomass or MSW incineration, the high temperatures and longer residence time of cement kilns allows for a more complete combustion of fuel, thus reducing air emissions. Unlike incineration, the cement manufacturing process produces limited residual waste, as nearly all non-combusted material is incorporated into the clinker (The Pembina Institute and Environmental Defence, 2014).
- The amount of biomass co-fired in cement plants (~6% of total thermal input) is small when compared to quantities of fossil fuels (~84%) and fossil and mixed waste (~10%) used (WBCSD, 2014).
- Industry data also show that the fraction of thermal energy supplied by biomass grew almost seven times, from 2000 to 2014, which indicates increasing world-wide adoption of biomass as a fuel in cement production.
- The carbon intensity of the fuel mix has decreased from 89.6 g-CO_2/MJ (for producing grey clinker) in 2000 to 85.8 g-CO_2/MJ in 2014 (WBCSD, 2014).[9]Increased use of biomass in cement plants would further lower the carbon intensity because biomass CO_2 emissions are considered neutral under the IPCC and CO_2 and energy accounting reporting standards for the cement industry (WBCSD, 2011).
- Four CO_2 capture technologies were tested using real flue gas at the Norcem cement plant in Brevik, Norway (Bjerge & Brevik, 2014), with a goal of evaluating technologies for capturing 400,000 t CO_2/y (around 50% of the plant's total CO_2 emissions).
- By 2030, Norcem plans to achieve zero-life cycle CO_2 emissions from its concrete products through a combination of CCUS and the use of biomass energy for cement production (around 30% of the fuel used at Norcem is derived from biomass) (Bergsli, 2017).
- CO_2 capture at the Norcem cement plant is one of the three industrial CCUS projects selected by Norway for detailed concept/front end engineering and design (FEED) studies.

[9] The CO_2 intensity of solid biomass is higher than that from fossil fuels. The IPCC default emission factor for solid biomass is 110 g-CO_2/MJ. Wood waste has an emission factor of 112 g-CO_2/MJ, and the biomass fraction of MSW has an emission factor of 100 g-CO_2/MJ (on a lower heating value basis). CO_2 from biomass is not accounted for in typical protocols and standards, but the quantities are relevant when designing a CO_2 capture and storage/utilization system to handle the CO_2. [http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf]

5.2 Summary of Economic Analyses

Co-firing

- The total installed costs of biomass power generation and co-firing technologies varies significantly by technology, feedstock price, location, and country.
- As such, costs for co-firing biomass at low levels have also been reported in the range of $400-600/kW with investment costs ranging between $140-850/kW (IRENA, 2012).
- Retrofitting existing pulverized coal power plants to co-fire biomass increases both capital (additional equipment needed for handling biomass) and operational (e.g., biomass fuel) costs.
- The co-firing of 10% biomass (by heat content) in a 550 MW power plant is estimated to increase the cost of electricity by 31% for hybrid poplar co-firing, and 14% for co-firing forest residues (Skone & James, 2012). The O&M cost of fuel is the biggest contributor to the increase in the cost of electricity (Skone & James, 2012).
- The additional capital expenditure required for the biomass co-firing was estimated to be $230/kW (2007$) (Skone & James, 2012).

Fischer-Tropsch fuels

- CBTL configurations with CO_2 capture require the selling price (RSP) of the F-T products (e.g., jet fuel) to be more than the spot price of conventional jet fuel (DOE/NETL-2012/1563; DOE/NETL-2015/1684)[10].
- Higher levels of biomass input further increase the product cost. The use of torrefied biomass lowered the RSP, whereas gasifying the biomass in a separate gasifier increased the RSP.

Ethanol

- The cost of capturing CO_2 from the ethanol fermentation step is low because the gas stream needs to be only dried and compressed (no amine capture unit is needed).
- The range of estimated costs of capturing fermentation CO_2 emissions is $10/t CO_2 to $22/t CO_2 (without transportation and storage costs) (IEAGHG, 2011).

Pulp and paper

- Biogenic CO_2 emissions are considered neutral under the European Union's ETS.
- Industrial facilities emitting biogenic CO_2 are not required to purchase CO_2 credits to offset their biogenic CO_2 emissions. On the flip side, EU facilities also do not receive preferential credits for capturing the biogenic CO_2.
- Studies indicate that the cost of avoiding 69-90% of CO_2 emissions from a kraft pulp mill would be around $72 to $70/metric tonne of CO_2 respectively (IEAGHG, 2016).
- For an integrated kraft pulp and board mill, the avoided CO_2 emission costs for 62% to 74% capture would be $91 to $98/t CO_2 respectively (IEAGHG, 2016). These are significant costs,

[10] RSP is the minimum price at which the products need to be sold to recover the annual revenue requirement of the plant, which includes the operating costs, debt service (interest), and revenue to provide the expected rate of return for the investors. It is assumed that 50% of the project capital costs were financed by debt service at an interest rate of 8%. The internal rate of return on equity was assumed to be 20% in the DOE/NETL-2012/1563 report.

because the break-even cost of pulp production is increased by around 30% in the case of capturing 90% of CO_2 emissions from a standalone kraft pulp mill.

Cement

- From a plant operator's perspective, the use of biomass in cement plants is affected by market conditions. When there is abundant supply of cement, a plant can afford to lose some production to minimize energy costs. When the market is sold-out, any loss in clinker output would negatively impact the plant profitability, negating the advantage of using alternative fuels with higher moisture and lower energy content (Abbas & Jun, 2015).
- For cement plants already co-firing biomass, the costs of installing a CO_2 capture system would be mostly similar to cases without biomass co-firing.
- The cost of retrofitting a cement plant in Norway with amine-based post-combustion CO_2 capture was estimated to be around $51/t CO_2 (Barker, 2013).

Waste incineration

- Waste can either be landfilled or incinerated. In countries with low landfill tipping fees, it would not be feasible to add the costs of CO_2 capture to an already expensive WtE plant without receiving some credits or revenues from the captured CO_2.
- Tang, Ma, Lai, and Chen (2013) showed by LCA of MSW combustion scenarios in China that oxy-fuel capture has both better efficiency and environmental impacts than MEA-based post-combustion capture. (Klein, et al., Klein, Zhang, & Themelis, 2003)
- Klein, et al. (Klein, Zhang, & Themelis, 2003) estimated the costs of oxycombustion-based CO_2 capture on a WtE plant, and found that the breakeven landfill tipping fee for the project to be feasible was around $59/ton of MSW.

5.3 Study Recommendations

A summary of the Recommendations developed by the Technical Group Task Force arriving from the Technical Summary of Bioenergy Carbon Capture and Storage document:

- Focus resources on education of policy makers with respect to the benefits of BECCS market opportunities, opportunities for EOR and negative carbon emissions.
- Perform research to develop and identify biomass feedstocks that require limited processing.
- Perform continued research to develop and identify new capture technologies that will have a substantially lower cost of electricity and address the unique flue gas compositions from bioenergy applications.
- Support regional organizations to track and monitor feedstock availability to insure sufficient quantities can be provided for continuous power generation.
- Incentivising the double benefit of BECCS can help avoid direct investment competition with other abatement options. Concerted efforts, e.g., global forest protection policies, carbon stock incentives, and bioenergy/renewable energy incentives, are necessary to avoid undesirable LUC emissions (Wise, et al., 2009; Clarke, et al., 2014).

- Early BECCS projects should aim to use mainly “additional” biomass and 2nd generation biofuel crops to avoid adverse impacts on land use and food production (Smith, et al., 2014). However, additional biomass is likely to be costlier due to, for example, increased irrigation.
- BECCS options that optimize water use and carbon footprint need to be identified through careful selection of crops, location, cultivation methods, pre-treatment processes, and biomass conversion technologies. Sustainable biomass feedstocks will require avoidance of unsustainable harvesting practices, e.g., exceeding natural replenishment rates (IPCC, 2014). Using “additional biomass” to avoid sustainability issues also helps improve public acceptance (Searchinger and Heimlich, 2015).
- Sustainability needs to be ensured across the whole BECCS chain. Improving pre-treatment processes for biomass (i.e., densification, dehydration, and pelletisation) will make biomass transport more efficient and remove geographical limitations of biomass supply (Hamelinck, et al., 2005; Luckow, et al., 2010).

Public Perception

- BECCS project developers and advocates should focus more on building up trust with the general public and local communities (Upham and Roberts, 2010) instead of just providing educational information.
- Stronger collaboration and exchange of ideas between stakeholders of the CCUS, bioenergy, and BECCS industries would also be beneficial and are recommended.

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TECHNICAL GROUP

Action Plan Status

Background

At the Regina meeting in June 2015, a working group was formed to develop and prioritize potential new Action Plan activities. The working group presented its recommendations at the Riyadh meeting in November 2015, which resulted in three new task forces being formed in the areas of Offshore CO_2-EOR, Improved Pore Space Utilisation, and Bioenergy with CCS. At the Tokyo meeting in October 2016 a task force on CCS for Industries was formed and at the Abu Dhabi meeting in December 2017 a task force on Hydrogen with CCS was formed.

Additionally, at the 2017 CSLF Mid-Year Meeting in April 2017, a working group (led by Norway) was 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.

This paper, prepared by the CSLF Secretariat, incorporates findings by the 2017 working group and 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 March 2018)

Current Actions

- Improved Pore Space Utilisation (*Task Force co-chairs: Australia and United Kingdom*)
- Bio-energy with CCS (*Task Force chair: United States*)
- CCS for Industries *(Task Force chair: France)*
- Hydrogen with CCS *(Task Force Chair: Norway)* (*Note: Task Force is currently in place only for Phase 0 activities.*)

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*)

- 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*)

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DRAFT

MEETING SUMMARY
Projects Interaction and Review Team (PIRT) Meeting
Abu Dhabi, United Arab Emirates
03 December 2017

Prepared by the CSLF Secretariat

LIST OF ATTENDEES

PIRT Active Members

Australia:	Andrew Barrett (Chair), Max Watson
Canada:	Eddy Chui, Mike Monea
China:	Jinfeng Ma
France:	Didier Bonijoly, Dominique Copin
Japan:	Ryozo Tanaka, Jiro Tanaka
Korea:	Chong Kul Ryu, Chang-Keun Yi
Mexico:	Jazmín Mota
Netherlands:	Harry Schreurs
Norway:	Lars Ingolf Eide, Åse Slagtern (Technical Group Chair)
Saudi Arabia:	Ammar AlShehri
South Africa:	Noel Kamrajh, Landi Themba
United Kingdom:	Brian Allison
United States:	Mark Ackiewicz
IEAGHG:	Tim Dixon

Other CSLF Delegates

Romania:	Constantin Sava, Anghel Sorin
United Arab Emirates:	Fatma AlFalasi, Reshma Francy

CSLF Secretariat Richard Lynch

Invited Speaker

Max Watson (*CO2CRC, Australia*)

Observers

Japan:	Leandro Figueiredo (*JANUS*)
Norway:	Arne Graue (*University of Bergen*)
Saudi Arabia:	Robert Dibble (*KAUST*)
	Feraih Alenuzey (*KACST*)
United Kingdom:	Brendan Beck (*Consultant to World Bank*)
	Ceri Vincent (*CO_2 GeoNet*)
United States:	Damien Beauchamp and Bill Brown (*NET Power*)
	John Harju and Ed Steadman (*University of North Dakota Energy and Environmental Research Center*)

DRAFT

1. Welcome

PIRT Chairman Andrew Barrett welcomed participants to the 28th meeting of the PIRT and thanked the United Arab Emirates Ministry of Energy and Industry for hosting the meeting. Mr. Barrett stated that the agenda was a busy one that included review of one project nominated for CSLF recognition and a preview of the new 2017 CSLF Technology Roadmap (TRM). Additionally, there would be an update on possible future activities for the CSLF Technical Group and a review of recommended changes to the PIRT's Terms of Reference document.

2. Introduction of Meeting Attendees

PIRT meeting attendees introduced themselves. In all, fifteen 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 Tokyo PIRT Meeting

The Meeting Summary from the April 2017 PIRT meeting in Abu Dhabi was approved as final with no changes.

5. Report from CSLF Secretariat

Richard Lynch provided a brief two-part report from the Secretariat, which covered the status of CSLF-recognized projects and outcomes from the April 2017 PIRT meeting.

Concerning the portfolio of CSLF-recognized projects, Mr. Lynch stated that as of December 2017 there were 33 active projects and 20 completed projects spread out over five continents, though this would change based on outcomes from the current meeting. For the current meeting, one new project had been proposed for CSLF recognition.

Mr. Lynch reported the following outcomes from the Abu Dhabi meeting:

- The PIRT recommended approval by the Technical Group for three projects:
  - Al Reyadah CCUS Project
  - National Risk Assessment Partnership
  - Carbon Capture Simulation Initiative / Carbon Capture Simulation for Industry Impact
- A mostly-final draft of the TRM was completed and sent to CSLF delegations for review and comments.
- The PIRT's new project engagement initiative has produced useful information, but this is only a starting point.

There also had been two actions from the meeting (both of which were completed):

- A working group consisting of the PIRT Chair, Technical Group Chair, Communications Task Force Chair, and Secretariat was established to review the CSLF and PIRT Terms of Reference documents to clarify project qualifications for CSLF recognition.

- The Secretariat was asked to revise the Project Engagement survey form to ask project sponsors why they had sought CSLF recognition and what benefits they expected from such recognition.

6. Preview of 2017 TRM

The TRM editor, Lars Ingolf Eide, gave a short presentation that previewed the new 2017 TRM. The Working Group for updating the TRM was chaired by Australia with representation from Norway, Canada, South Africa, the United Kingdom, the United States, the IEAGHG, and the CSLF Secretariat. In addition, there were contributions from several international experts on CCS. The overall approach was to refresh the structure and content of the 2013 TRM as needed, in order to keep the overall level of effort to a manageable level.

Mr. Eide briefly described the main changes from the 2013 TRM:

- New time horizons are being used for medium- and long-term recommendations and targets (2025 and 2035 respectively, instead of the previous TRM's target dates of 2030 and 2050).
- The "Background" chapter was revised to reflect COP21 targets, and quantitative targets which meet the IEA 2 ºC scenario were used for CO_2 capture and storage.
- A new section was included on non-technical measures such as regulations, and there is expanded discussion on CCS, CCU, and CCUS. In the 2017 TRM, CCUS was defined as a subset of CCS.

Mr. Eide stated that the main finding of the 2017 TRM is that CCS has been proven to work and has been implemented in power and industrial settings. However, there needs to be a sense of urgency to drive any action. Also, substantial investment in CCS and other low-carbon technologies is needed to achieve the targets of the Paris Agreement. Main barriers to implementation are inadequate government investment and policy/support incentives as well as uncertainties and risk that are stifling private sector investment. Rapid deployment of CCS is critical in the industry and power sectors, and negative CO_2 emissions can be achieved by using a combination of biomass and CCS. Finally, costs and implementation risks can be reduced by developing industrial clusters and CO_2 transport and storage hubs.

Mr. Eide stated that there are many priority recommendations made by the TRM:

- Based on the Paris Agreement's 2 ºC scenario, governments and industry should work together to contribute to the COP21 targets by implementing sufficient large-scale projects in the power and industry sectors to achieve:
    - Long-term isolation from the atmosphere of at least 400 megatonnes (Mt) of CO_2 per year by 2025 (or have permanently captured and stored 1,800 Mt CO_2); and
    - Long-term isolation from the atmosphere of at least 2,400 Mt CO_2 per year by 2035 (or have permanently captured and stored 16,000 Mt CO_2).
- In order to achieve these goals, CSLF members recommend the following actions to 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 entire CCS chain through RD&D;
- Accelerate CCS in developing countries by funding storage appraisals and technology readiness assessments; and
- Facilitate implementation of CO_2 utilization.

Mr. Eide concluded his presentations by summarizing the TRM's key message to CSLF Ministers: Governments have a critical role in accelerating the deployment of CCS.

7. Recommended Updates to PIRT and CSLF Terms of Reference

Mr. Lynch provided background for this agenda item by stating that at the May 2017 CSLF Mid-Year Meeting, the CSLF Policy Group requested that the CSLF Technical Group and the CSLF Communications Task Force review and update CSLF project recognition procedures. The issue was that project recognition was described in both the CSLF Terms of Reference and the PIRT Terms of Reference, and the language in these documents did not agree with each other. In the months following the 2017 Mid-Year Meeting, a working group consisting of the Technical Group Chair and Vice Chairs, PIRT Chair, Communications Task Force Chair, and CSLF Secretariat extensively reviewed both Terms of Reference documents and recommended changes which fell into three categories: (a) updating project recognition procedures; (b) consistency with the CSLF Charter; and (c) other miscellaneous corrections and updates. Mr. Lynch stated that the result of the working group's efforts were marked up versions of both Terms of Reference documents, and that recommended changes to the CSLF Terms of Reference were to be addressed by the Policy Group at its meeting.

There was much ensuing discussion about the changes proposed for the PIRT Terms of Reference. In the end, the changes recommended by the working group were all accepted, but during the discussion other changes were proposed by Ryozo Tanaka, Didier Bonijoly, and Harry Schreurs and these were also accepted. The Secretariat was asked to produce a new version of the document that incorporates all of the changes. (*Note: the revised PIRT Terms of Reference is appended to the end of this Summary.*)

8. Review and Approval of Project Proposed for CSLF-Recognition: CO2CRC Otway Project Stage 3

Max Watson, representing project sponsor CO2CRC, gave a technically detailed presentation about the Otway Stage 3 project. 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.

Outcome: After a discussion which clarified some of the details about the project, there was unanimous consensus by the PIRT to recommend approval of the CO2CRC Otway Project Stage 3 by the Technical Group. Project nominators are Australia (lead), Canada, France, Mexico, Norway, Saudi Arabia, and the United Kingdom.

9. Update from Working Group on Evaluating Existing and New Ideas for Possible Future Technical Group Activities

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.

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. There are currently four active task forces besides the PIRT: Improved Pore Space Utilization (co-chaired by Australia and the United Kingdom), Bioenergy with CCS (chaired by the United States), Industrial CCS (chaired by France), and Offshore CO_2-EOR (chaired by Norway and which completed its activities in 2017). Ms. Slagtern stated that there are eleven 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. Additionally, there have been eleven other actions which were completed between 2006 and 2015 and have resulted in task force final reports.

The current working group chair, Lars Ingolf Eide, then described the process for developing and prioritizing a long list of future potential actions. In all, 24 potential new topics were included – eleven unaddressed items from 2015, eleven past task force topics (for possible updates), and two new proposals. The members of the working group then participated in a preference poll which resulted in 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

Mr. Eide stated that for the proposed action on Hydrogen as a Tool to Decarbonize Industries, the working group had come up with several sub-topics that could be addressed: hydrogen production and use; hydrogen with CCS, synergies with renewables, life cycle costs and carbon footprint; and hydrogen value chain. Additionally, there are several existing activities and programs – in Europe, Japan, and the United States as well as with multinational energy companies such as Statoil, Gasunie, and Vattenfall Nuon – which could be mapped in a "Phase 0" of a new Technical Group task force. Ensuing discussion emphasized the need to make linkages with existing efforts that have already been funded and that this "mapping" effort needs to be accomplished before a new task force can effectively move forward. Since this is not a PIRT activity, further discussion was deferred until the next day's meeting of the full Technical Group.

DRAFT

10. General Discussion and New Business

Mr. Eide suggested that the PIRT should find ways on how to measure CCUS progress in light of current TRM recommendations. He also suggested 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. Volunteers include Australia (Andrew Barrett), Canada (Mike Monea), Norway (Lars Ingolf Eide), the United Kingdom (Brian Allison), the United States (Mark Ackiewicz), the Technical Group Chair (Åse Slagtern), and the CSLF Secretariat (Richard Lynch).

11. Adjourn

Mr. Barrett thanked the attendees for their interactive participation, expressed his appreciation to the host United Arab Emirates Ministry of Energy and Industry, and adjourned the meeting.

Summary of Meeting Outcomes

- The PIRT has recommended approval by the Technical Group for the CO2CRC Otway Project Stage 3.
- The 2017 TRM is completed and has been launched.
- The PIRT's Terms of Reference document has been revised in order to update project recognition procedures, become consistent with the CSLF Charter, and fix other miscellaneous inaccuracies.
- A PIRT working group was organized to explore and suggest approaches for tracking follow-up and progress of the TRM recommendations. The group should also explore the feasibility of utilizing expertise and learnings from CSLF-recognized projects as input to future editions of the TRM.

Actions

- The CSLF Secretariat will produce a new version of the PIRT Terms of Reference which incorporates all agreed changes. (*Note: the new version is appended below*.)

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.

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.

Carbon Sequestration Leadership Forum
www.cslforum.org

Active and Completed CSLF Recognized Projects

(as of April 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

Nominators: Canada (lead) and United States

This is a large-scale project in northeastern British Columbia, Canada, which will permanently sequester approximately two million tonnes per year CO_2 emissions from a large natural gas-processing plant into deep saline formations of the Western Canadian Sedimentary Basin (WCSB). Goals of the project are to verify and validate the technical and economic feasibility of using brine-saturated carbonate formations for large-scale CO_2 injection and demonstrate that robust monitoring, verification, and accounting (MVA) of a brine-saturated CO_2 sequestration project can be conducted

cost-effectively. The project will also develop appropriate tenure, regulations, and MVA technologies to support the implementation of future large-scale sour CO_2 injection into saline-filled deep carbonate reservoirs in the northeast British Columbia area of the WCSB.
Recognized by the CSLF at its London meeting, October 2009

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
Nominators: Canada (lead) and United States
This is a pilot-scale project that involves utilization of acid gas (approximately 70% CO_2 and 30% hydrogen sulfide) derived from natural gas extraction for enhanced oil recovery. Project objectives are to predict, monitor, and evaluate the fate of the injected acid gas; to determine the effect of hydrogen sulfide on CO_2 sequestration; and to develop a "best practices manual" for measurement, monitoring, and verification of storage (MMV) of the acid gas. Acid gas injection was initiated in December 2006 and will result in sequestration of about 25,000 tons (or 375 million cubic feet) of CO_2 per year.
Recognized by the CSLF at its Paris meeting, March 2007

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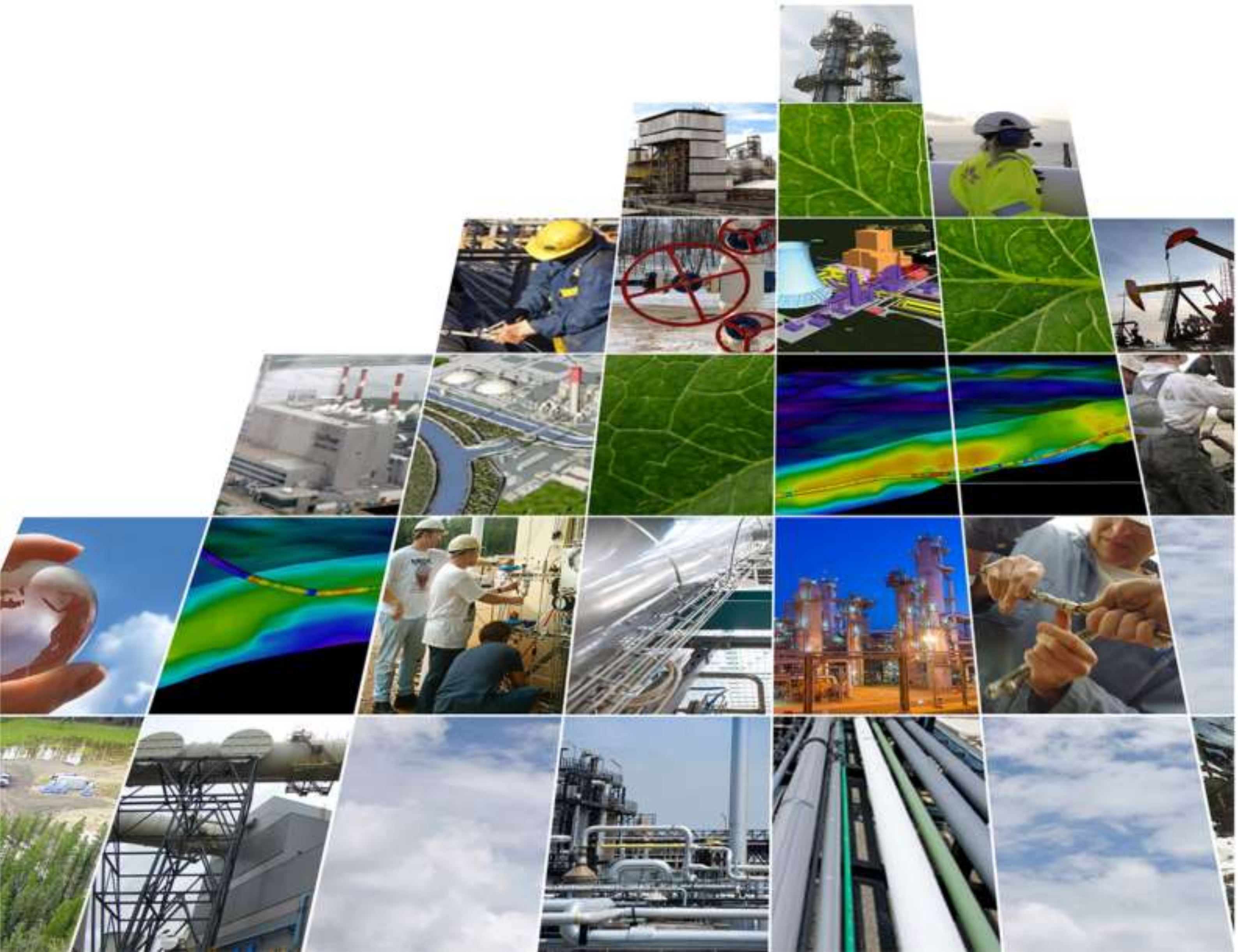
Carbon Sequestration

TECHNOLOGY ROADMAP



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Executive Summary

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

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

Key Findings

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

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

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

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

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

Priority Recommendations

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

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

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

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

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

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

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

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1. Introduction

1.1. Objective and audience

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

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

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

1.2. Background

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

1.3. Terminology

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

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

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

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

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

1.4. Major differences between 2013 and 2017 roadmaps

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

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

2. The Importance of Deploying CCS

2.1. The need to reduce CO_2 emissions

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

> ***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.

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

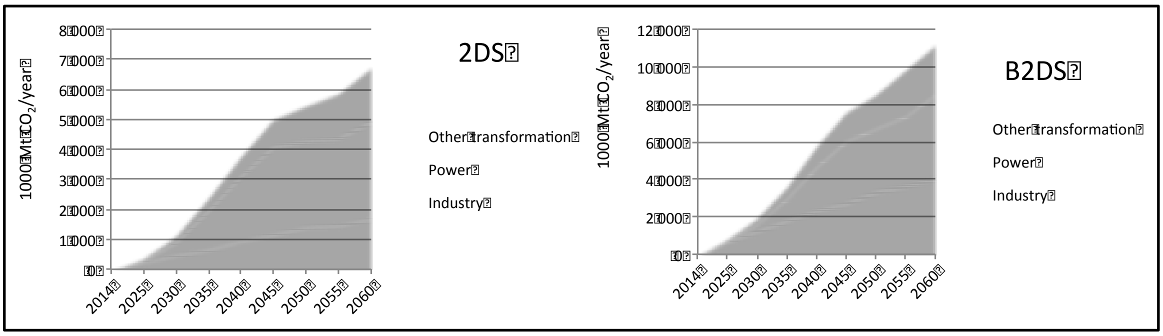

Figure 2.1. *CO_2 captured and stored per year to achieve the 2°C Scenario (left panel) and Beyond 2°C Scenario (right panel), in 1,000 Mt CO_2/year (after IEA 2017a).*

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).

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.

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

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

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

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

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

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

3.1.4. Hydrogen as a mechanism to decarbonize industries

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

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

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

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

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

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

3.1.5. Addressing technology needs

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

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

Costs for CO_2 capture can be reduced through the following:

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

Learning from experience

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

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

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

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

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

Novel/emerging/innovative/transformative subsystem technologies

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

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

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

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

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

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

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

3.1.6. Recommendations for CO_2 capture

Towards 2020:

Governments and industry should work together to:

- Reduce the avoided carbon cost (or capture cost) in dollars per tonne of CO_2 ($/t$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.

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 $/t$CO_2$ (or capture cost) at least 40% below that of 2016 commercial technologies, while at the same time minimizing environmental impacts.
- Fund promising 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

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

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

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

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

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

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

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

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

3.2.2. Hubs and clusters

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

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

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

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

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

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

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

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

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

3.2.3. Recommendations for CO_2 transport and infrastructure

Towards 2020:

Governments and industry should work together to:

On transport

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

On infrastructure

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

Towards 2025:

Governments and industry should work together to:

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

Towards 2035:

Governments and industry should work together to:

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

3.3. Storage

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

Table 3.1. Projects with pure geological storage

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

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

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

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

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

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

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

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

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

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

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

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

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

3.3.1. Identified technology needs

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

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

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

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

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

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

3.3.2. Recommendations for CO_2 storage

Towards 2020:

Governments and industry should work together to:

On large-scale CO_2 storage

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

On monitoring and mitigation/remediation

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

On understanding the storage reservoirs

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

Towards 2025:

Governments and industry should work together to:

On large-scale CO_2 storage

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

On monitoring and mitigation/remediation

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

Towards 2035:

Governments and industry should work together to:

On large-scale CO_2 storage

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

On monitoring and mitigation/remediation

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

3.4. CO_2 utilization, including enhanced hydrocarbon recovery

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

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

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

There are several forms of CO_2 reuse, or CCU, already in use or being explored, including urea production, ethylene oxide production, ethanol production, utilization in greenhouses, conversion to polymers, methanol and formic acid production, production of bioplastics, and the cultivation of algae as a pathway to bioenergy animal feed, as well as other products. These will not lead to permanent storage but may contribute to reduced CO_2 emissions; for example, if the captured CO_2 replaces new, fresh hydrocarbons as source for carbon. Also, there may be other related benefits: as an example, the utilization of waste CO_2 in greenhouses in the Netherlands already leads to a better business case for renewable heating and a rapid growth of geothermal energy use in the sector. These options could lead to a reduction in capture costs and transport optimization and learnings.

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

For many of the CCUS and, in particular, CCU options, the total amount of CO_2 that can be permanently stored is, for all practical and economic purposes, limited (Mac Dowell et al. 2017). CO_2-EOR has the largest potential of the various CO_2 utilization options described, and it has not been sufficiently explored to date as a long-term CO_2 storage option. So far, only the CO_2-EOR Weyburn-Midale project in Canada; the CO_2-EOR Project at the Bell Creek field in Montana; the CO_2-EOR project at Cranfield site in Mississippi; and the Farnsworth, Texas, project have performed extensive monitoring and verification of CO_2 stored in EOR operations.

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

The lack of scalability and the economic challenges are significant barriers to the deployment of CO_2 utilization technologies in the near and long term (NCC 2016). However, in some countries utilization provides early opportunities to catalyze the implementation of CCS. In this way, the CO_2 utilization pathways can form niche markets and make a contribution to paving the way for commercial CCS. This applies not only to oil-producing countries but also to regions with evolved energy systems that will allow the implementation of feasible CO_2 business cases.[16]

3.4.1. Identified technology needs

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

- Improving the understanding of how to increase and prove the permanent storage of CO_2 in CO_2-EOR operations. CSLF (2013b) points out the similarities and differences between CO_2-EOR and CO_2 injected for storage. One conclusion from this report is that there are no technical challenges per se in converting CO_2-EOR operations to CCS, although issues like the availability of high-quality CO_2 at an economic cost and in appropriate volumes; infrastructure for transporting CO_2 to oil fields; and legal, regulatory, and long-term liability must be addressed.
- Make offshore CO_2-EOR economic, including the following (CSLF 2017b):
  - Making sufficient CO_2 available; e.g., by building transport infrastructure that connects sources with reservoirs.
  - Supporting RD&D to develop and qualify new technologies.
  - Developing business models for offshore CO_2-EOR.
  - Improving volumetric sweep. Due to different well configuration in offshore fields compared with onshore EOR, alternative methods for are needed. Optimal well placement and mobility controls of CO_2 are instrumental for success.
  - Expanding experience from offshore EOR needs beyond the Lula project in Brazil.
  - Proving offshore CO_2-EOR economically viable.
- Improving the understanding of how to increase and prove the permanent storage of CO_2 in EGR, ECBM, EGHR, enhanced shale gas recovery, and other geological applications of CO_2.
- Developing and applying carbonation approaches (i.e., for the production of secondary construction materials).
- Developing large-scale, algae-based production of fuels and animal feed to offset primary fuel consumption and decrease agricultural cultivation practices, which might have a large CO_2 footprint.
- Improving and extending the utilization of CO_2 in greenhouses to increase the biological processes for photosynthesis, investigating marine algae cultivation for wide-scale biomass

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

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

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

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

3.4.2. Recommendations for CO_2 utilization

Towards 2020:

Governments and industry should work together to:

- Resolve regulatory and technical challenges for the transition from CO_2-EOR operations to CO_2 storage operations. There may be value in experiences from reporting requirements for CO_2 operations that are claiming credits under the 45Q tax credit in the United States. [18]
- Research, evaluate, and demonstrate carbonation approaches, in particular for mining residue carbonation and concrete curing, but also other carbonate mineralization that may lead to useful products (e.g., secondary construction materials), including environmental barriers such as the consequences of large mining operations and the disposal of carbonates.
- Support research and development pathways for the development of novel catalysts using abundant materials and advanced manufacturing techniques to produce nanocatalysts to bring down costs.
- Support RD&D on subsea separation and improved mobility control.
- Map opportunities, conduct technology readiness assessments, and resolve main barriers for the implementation of the CO_2 utilization family of technologies, including benchmarked life cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 reuse pathway and the energy requirement of each technology using technological modeling.

Towards 2025

Governments and industry should work together to:

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

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

4. Summary

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

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

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

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

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

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

5. Priority Actions Recommended for Implementation by Policymakers

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

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

This may be achieved through the following actions:

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

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

6. Follow-Up Plans

The CSLF should continue to be a platform for an international coordinated effort to commercialize CCS technology working with, among others, the IEA, the GCCSI, and the IEA Greenhouse Gas R&D Programme.

The CSLF should continue to monitor progress in light of the identified priority actions, report the findings at Ministerial meetings, and suggest adjustments and updates of the technology roadmap. It is recommended that the CSLF, through its Projects Interaction and Review Team (PIRT), monitor progress in CCS made in relation to the recommended priority actions. Through the CSLF Secretariat, the PIRT will:

- Solicit input with respect to progress of CCS from all members of the CSLF.
- Gather information from a wide range of sources on the global progress of CCS, including collaboration partners.
- Prepare a simple reporting template that highlights the progress made in relation to the priority actions.
- Report annually to the CSLF Technical Group
- Report biennially, or as required, to the CSLF Ministerial Meetings.

The PIRT should continue to have the responsibility for future updates of the CSLF technology roadmap.

7. Acknowledgements

This technology roadmap was prepared for the CSLF Technical Group by an editorial committee under the auspices of the CSLF Projects Interaction and Review Team. The committee was chaired by Andrew Barrett, Australia, and had members from the United Kingdom (Brian Allison), Canada (Eddy Chui), South Africa (Tony Surridge), the United States (John Litynski), The International Energy Agency Greenhouse Gas R&D Programme (Tim Dixon), and Norway (Lars Ingolf Eide). The CSLF Secretariat (Richard Lynch) and the CSLF Technical Group Chair Åse Slagtern (Norway) have also taken active part in the discussions. The first draft of the technology roadmap was sent to a large number of international experts, and the following individuals contributed comments and input:

Norway: Philip Ringrose, Sveinung Hagen, Jørg Aarnes, Jens Hetland, Arvid Nøttvedt, Grethe Tangen, Mario Ditaranto, Svein Gunnar Bekken, Jørild Svalestuen, Svend Tollak Munkejord, Arne Dugstad, Hans Aksel Haugen, Partow Partel Henriksen, John Kristian Økland, and Tore Andreas Torp

United States: John Thompson

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South Africa: Sibbele Heikamp

Australia: Paul Feron

Japan: Takayuki Higahsii

Global Carbon Capture and Storage Institute

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Several CSLF Technical Group delegates, as well as observers from the International Energy Agency and Global Carbon Capture and Storage Institute, took supplied corrections and suggestions for improvement in the next-to-final draft.

Annex A. Abbreviations and Acronyms

\$/tCO_2	dollars per tonne of carbon dioxide
2DS	2°C Scenario
B2DS	Beyond 2°C Scenario
CSLF	Carbon Sequestration Leadership Forum
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCUS	carbon capture, utilization, and storage
CDM	Clean Development Mechanism
CO_2	carbon dioxide
CO_2-EOR	carbon dioxide-enhanced oil recovery
DOE	US Department of Energy
ECBM	enhanced coal bed methane production
E&A	exploration and appraisal
EGHR	enhanced gas hydrate recovery
EGR	enhanced gas recovery
EOR	enhanced oil recovery
EWR	enhanced water recovery
GCCSI	Global Carbon Capture and Storage Institute
H_2	hydrogen
IEA	International Energy Agency
ISO	International Organization for Standardization
km	kilometer
M&V	monitoring and verification
MPE	Norwegian Ministry of Petroleum and Energy
MW	megawatts (10^6 watts)
Mt	megatonnes (10^6 tonnes)
OECD	Organisation for Economic Co-operation and Development
PIRT	Projects Interaction and Review Team
ppm	parts per million
RD&D	research, development and demonstration
RTS	Reference Technology Scenario
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants

Annex B. Summary of Technical Recommendations

Towards 2020:

Governments and industry should work together to:

On capture

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

On transport and infrastructure

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

On storage

- Identify, characterize, and qualify CO_2 storage sites for large-scale systems.
- Maintain momentum for the Large-Scale Saline Storage Project Network, which was announced at the sixth CSLF Ministerial Meeting in Riyadh, Saudi Arabia, in November 2015, and which was proposed to leverage international saline storage projects that can share best practices, operational experience, and lessons learned to advance CCS deployment.
- Accelerate learning and technology development by sharing subsurface, well, and other relevant data and knowledge; for example, in initiatives such as the CO_2 Storage Data Consortium, an open, international network developing a common platform for sharing data sets from pioneering CO_2 storage projects.

- Fund RD&D activities to close technology gaps and validate the methods/technologies in case studies to accelerate the pace of CCS deployment.
- Facilitate synergies with other technologies; for example, geothermal and other relevant renewables.
- Facilitate research into the interface between transport and storage.
- Undertake regional appraisal programs with dynamic calibration and matched source-sink scenario analysis.
- Identify the sites for CO_2 storage that are most likely to work, including in developing nations.
- Improve CCS narratives around CO_2 storage, costs, and CO_2 containment risks.
- Increase public communication on CO_2 storage projects to improve the communication and dissemination of this technology and to increase knowledge and acceptance with the general public—to gain a social license to operate
- Fund activities that continue to drive down costs for existing monitoring technologies and techniques, and the development, demonstration, and validation of new measuring and monitoring techniques and sensors, onshore and offshore. This includes for leakage in terms of anomaly detection, attribution, and leakage quantification.
- Fund development and demonstration of monitoring strategies to optimize monitoring and make monitoring more cost-efficient for large-scale projects.
- Fund development and verification of mitigation and remediation methods and corrective actions for leakage, including well leakage, and test in small-scale, controlled settings.
- Identify minimum requirements/objectives for monitoring and verification (M&V) programs, both onshore and offshore, to inform fit-for-purpose legislation and regulations.
- Further advance and utilize simulation tools, with a focus on multiphase flow algorithms and coupling of fluid flow to geochemical and geomechanical models.
- Develop and agree on consistent methods for determining CO_2 storage capacity (dynamic) reserves at various scales (as opposed to storage resources), at various levels of project maturity, and with a global distribution of this capacity.
- Further improve dynamic CO_2 capacity assessment (e.g., Smith 2017).
- Further improve on well material (steel and cement) technologies to reduce cost and risk (such as corrosion).
- Enhance the ability to more precisely predict storage efficiency by using experience from successful injections (e.g., Sleipner and Snøhvit) and knowledge on geological complexity to improve models on reservoir injectivity and plume migration.
- Enable safe injection of large amounts of CO_2 by advancing reservoir models with respect to predicting pressure buildup, and avoid hydraulic fracturing.
- Recommend workflow for caprock and fault integrity studies in CO_2 storage sites, as well as measurements and geochemical modeling of sealing capacity.
- Develop a cost model that will help improve the CO_2 storage assessments.

Utilization

- Resolve regulatory and technical challenges for the transition from CO_2-EOR operations to CO_2 storage operations. There may be value in experiences from reporting requirements for CO_2 operations that are claiming credits under the 45Q[20] tax credit in the United States.
- Research, evaluate, and demonstrate carbonation approaches, in particular for mining residue carbonation and concrete curing, but also other carbonate mineralization that may lead to useful products (e.g., secondary construction materials), including environmental barriers such as the consequences of large mining operations and the disposal of carbonates.
- Support research and development pathways for the development of novel catalysts using abundant materials and advanced manufacturing techniques to produce nanocatalysts to bring down costs.
- Support RD&D on subsea separation and improved mobility control.
- Map opportunities, conduct technology readiness assessments, and resolve main barriers for the implementation of the CO_2 utilization family of technologies including benchmarked life cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 reuse pathway and the energy requirement of each technology using technological modeling.

Towards 2025:

Governments and industry should work together to:

On capture

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

On transport and infrastructure

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

On storage

- Facilitate exploration, characterization, and qualification of large-scale CO_2 storage sites (10–100 million tons CO_2 per year) in key regions of the world, building on experience from current projects and pilots and including use of existing oil and gas infrastructure.
- Facilitate qualification of CO_2 storage sites for safe and long-term storage in the scale of tens of millions of tonnes of CO_2 annually per storage site, linked to clusters of CO_2 transport systems.
- Ensure that all CSLF member countries have national storage assessments publicly available,
- Continue the development and execution of E&A portfolio programs in key potential storage basins.
- Develop robust conceptual workflow to assure regulators that site characterization meets international leading practice.

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

- Reduce monitoring and verification (M&V) overall costs by 25% in average from 2016 levels.

On utilization

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

Towards 2035:

Governments and industry should work together to:

On capture

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

On transport and infrastructure

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

On storage

- Reduce M&V costs by 40% from 2015 levels.

Annex C. References

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