carbon sequestration leadership forum

2017
Carbon Sequestration
TECHNOLOGY ROADMAP

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Executive Summary

The Carbon Sequestration Leadership Forum (CSLF) *Technology Roadmap 2017* aims to provide recommendations to Ministers of the CSLF member countries on technology developments that are required for carbon capture and storage (CCS)[1] 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 coming years are critical for large-scale deployment of CCS; therefore, a sense of urgency must be built to drive action.
- Substantial, and perhaps 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 industry and power sectors in both Organisation for Economic Co-operation and Development (OECD) and non-OECD countries, 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.
- 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.[2] 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

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[1] In this technology roadmap, carbon capture, utilization, and storage (CCUS) is considered a subset of CCS.

[2] 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.

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:

- 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 in total 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 in total 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 all or part of the CO_2 is used before all is being geologically stored for long-term isolation from the atmosphere . This may include instances in which CO_2 is used to enhance the production of hydrocarbon resources (such as CO_2-enhanced oil recovery) or in the formation of minerals or long-lived compounds from CO_2, thereby permanently isolating the CO_2 from entering the atmosphere.
- Carbon capture and utilization (CCU) is used when the CO_2 is stored only temporarily. This includes applications in which CO_2 is reused or used only once while generating some additional benefit. Examples are urea and algal fuel formation or greenhouse utilization.

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

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

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

1.4. Major differences between 2013 and 2017 roadmaps

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

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

2. The Importance of Deploying CCS

2.1. The need to reduce CO_2 emissions

Emissions Reduction Scenarios

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

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

In 2014 total energy-related direct global emissions of CO_2 amounted to approximately 34,200 megatonnes (Mt), of which 8,300 Mt CO_2/year were direct emissions from industry and 13,600 Mt CO_2/year were direct emissions from the power sector (IEA 2017a).[3]

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

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

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, 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).[4] 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.

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[4] 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

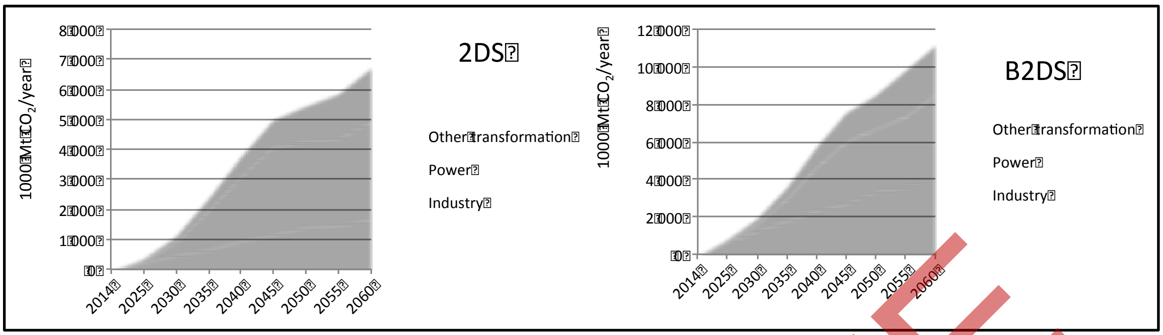

Figure 2.1. *CO_2 captured and stored per year to achieve the 2°C Scenario (left panel) and Beyond 2°C Scenario (right panel), in 1,000 Mt CO_2/year (after IEA 2017a).*

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.[5]

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[5] 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.[6] 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.[7] 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.

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[6] 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).

[7] 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).

- 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).
- 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.[8]

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

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[8] 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)[9] 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

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[9] 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.

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 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.[10] 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.

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[10] 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.”

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

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

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

3.1.6. Recommendations for CO_2 capture

Towards 2020:

Governments and industry should work together to:

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

Towards 2025:

Governments and industry should work together to:

- Fund and facilitate cross-border RD&D cooperation to bring to demonstration CO_2 capture technologies for power generation and industrial applications that have avoided cost in \$/tCO_2 (or capture cost) at least 40% below that of 2016 commercial technologies, while at the same time minimizing environmental impacts.

- Fund promising technology ideas to be tested and verified at pilot scale (1–10 MW range) and/or separating 0.01–0.1 Mt CO_2/year.

Towards 2035:

Governments and industry should work together to:

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

3.2. CO_2 infrastructure

Coping with the large volumes of CO_2 to be collected from future power plants and industrial clusters,[11] 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;[12] 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

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

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

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 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.[13]

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

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

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 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.[14]

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

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[14] 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.

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.

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.[15]

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:[16]

- 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.

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

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

  - Improved and fit-for-purpose well and reservoir technologies and management procedures, including well integrity.
- Storage integrity
  - 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 2ºC 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.

<u>**Towards 2035:**</u>

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.[17]

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[18] 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).

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[17] 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.

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

- 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 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. [19]
- 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.

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[19] 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:[20]

- Long-term isolation from the atmosphere of at least 400 Mt CO_2 per year by 2025 (or permanent capture and storage of in total1,800 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 in total 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.

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

6. Follow-Up Plans

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

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

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

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

7. Acknowledgements

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

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

United States: John Thompson

United Kingdom: Sarah Tennison and Jon Gibbins

South Africa: Sibbele Heikamp

Australia: Paul Feron

Japan: Takayuki Higahsii

Global Carbon Capture and Storage Institute

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

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[21] 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 \$/tCO_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.

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[21] 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.

- Develop robust conceptual workflow to assure regulators that site characterization meets international leading practice.
- 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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