Carbon Sequestration Leadership Forum

06 April 2017

www.cslforum.org

TECHNICAL GROUP

Draft 2017 CSLF Technology Roadmap

Background

At the Riyadh meeting in October 2015, a working group chaired by Australia was formed with the mandate to produce a new CSLF Technology Roadmap (TRM) in time for the 2017 CSLF Ministerial Meeting. The process chosen for the rewrite was to use the 2013 TRM as a basis and refresh its content as needed. An advanced draft of the 2017 TRM has been completed by the working group and was sent to Technical Group delegates for their review and comments.

The draft of the 2017 TRM follows this cover page.

Action Requested

The Technical Group is requested to review the draft of the 2017 CSLF Technology Roadmap. A firm deadline for receiving comments is July 1, 2017.

Carbon Sequestration Leadership Forum
Technology Roadmap 2017

Executive Summary

Carbon capture, utilisation and storage (CCUS) will be a major contributor to enable nations to meet their Paris Agreement targets. We know from experience that CCUS works in removing significant volumes of CO_2 from the atmosphere.

This latest version of the Carbon Sequestration Leadership Forum's Technical Roadmap highlights advances in capturing, storing and utilizing CO_2 since the 2013 update, and provides the nations of the world with a powerful way forward to a lower emission future.

Since the last full update of the CSLF TRM in 2013, there have been advances and positive developments in CCS, although at a lower rate than is necessary to achieve earlier objectives. New Large-Scale Integrated Projects (LSIPs) as well as demonstration scale projects have come into operation both in the power and industry sector and legislation has been put in place in some jurisdictions. The Roadmap has been updated in light of the outcomes of the COP21 meeting in Paris in November 2015. In particular, the importance of CCUS in industries other than power and the potential of achieving negative CO_2 emissions using a combination of biomass and CCUS is highlighted in the CSLF TRM 2017. The importance of bringing costs down by developing industrial clusters, and CO_2 transport and storage hubs is highlighted.

CCUS is not possible without the right policy settings and the appropriate financial framework. 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 Technical Roadmap demonstrates that CCUS works in the power industry, the gas processing industry, refineries, industries using biomass as raw material, and the enhanced oil recovery industry. This Roadmap also highlights that the implementation is well behind the trajectory to reach the stated goal from COP21 of being significantly below a 2°C temperature rise.

New time horizons for medium- and long-term recommendations and targets have been set to 2025 and 2035. This is more aggressive than the previous version as the CSLF recognizes that implementation needs to be stepped up.

Main Recommendations

Governments and industry should work together to contribute to the COP21 targets by implementing sufficient large-scale projects in the power and industry sectors to

- Permanently store 0.5 $GtCO_2$ /year by 2025 (or have permanently captured and stored 2 $GtCO_2$)
- Permanently store 2.7 $GtCO_2$ /year by 2035 (or have permanently captured and stored 20 $GtCO_2$)

To facilitate cost reductions and accelerated implementation sufficient to reach their targets Governments and industry should work together to:

- Develop supportive policy incentives, including equity considerations, recognition and support for CCS on similar terms as other low-carbon technologies
- Develop markets and business models for CCUS support
- Accelerate legal and regulatory frameworks for CCS, also on a regional scale (e.g. the London Protocol for transborder movement of CO_2 when considered as waste)
- Develop strategic clusters and hubs, in particular for industrial CCUS, and CO_2 transportation and storage infrastructures, including early identification and characterisation of potential storage sites

- Improve CCUS public outreach and education, aimed at amongst other, building trust, reducing and tackling misconceptions, and supporting educators as well as community proponents of CCUS projects
- Facilitate exchange of data from operating large scale projects
- Support RD&D for novel and emerging technologies along the whole CCUS chain to drive down costs
- Map opportunities, conduct technology readiness assessments and resolve main barriers for the implementation of the CO_2 utilisation family of technologies including life-cycle assessments and CO_2 and energy balances

1. Objective and audience

1.1 Objective

The objective of the Carbon Sequestration Leadership Forum (CSLF) Technology Roadmap (TRM) 2017 is to provide recommendations to Ministers of the CSLF countries on technology developments that are needed for Carbon Capture, Utilisation and Storage (CCUS) to fulfil the purpose of the CSLF.

The CSLF Charter, modified at the CSLF Ministerial-level meeting in Beijing in September 2011 to include 'CO_2 utilisation', states the following purpose of the organization:

"To accelerate the research, development, demonstration, and commercial deployment of improved cost-effective technologies for the separation and capture of carbon dioxide for its transport and long-term safe storage or utilisation; to make these technologies broadly available internationally; and to identify and address wider issues relating to CCUS. This could include promoting the appropriate technical, political, economic, and regulatory environments for the research, development, demonstration, and commercial deployment of such technology."

It is believed (IEA[1] 2016a,b,c; GCCSI[2] 2015a) that Carbon Capture and Storage (CCS) can significantly contribute to achieve the targets adopted at the Conference of the Parties 21st meeting (COP21) in Paris 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[3], 2016). The importance of CCS was pointed out by IPCC[4] (2014), which found that achieving 450ppm without CCS gets more far costly than for any other low carbon technology, by average of 138%. Furthermore, only four of 11 models could even achieve 450 ppm without CCS, emphasising that CCS is perhaps the most important low carbon energy technology.

With the TRM 2017 CSLF aspires to play an important role in reaching the COP21 targets by accelerating commercial deployment, as well as RD&D[5], of improved, and cost-effective technologies for the separation and capture of CO_2, its transport and its long-term safe storage or utilisation.

1.2 Audience

The audience for the recommendations derived in this Technical Roadmap (TRM) are energy policy developers in general and the CSLF Ministers in particular. The TRM is a product of the CSLF Technical Group that is delivered to the CSLF Policy Group to form the background for the communiqué from the CSLF Ministerial meeting 2017.

1.3 Update process

The CSLF TRM 2017 replaces the CSLF TRM 2013. The approach for changes was

- The CSLF Technical Group (TG) chair, co-chairs, task force leaders and Secretariat identified where changes from the TRM 2013 were needed

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[1] International Energy Agency
[2] Global Carbon Capture and Storage Institute
[3] United Nations Framework Convention on Climate Change
[4] Intergovernmental Panel on Climate Change
[5] Research Development and Demonstration

- A small editorial group set out to implement the changes for the capture (Norway), transport and infrastructure (Norway), storage (Australia with support from IEAGHG[6]) and utilisation (USA), with support from UK
- The first draft was sent to XX worldwide experts for comments and YY responses were received
- Comments were implemented by the editorial groups in the next to final draft
- The CSLF TG was given the opportunity to give input the next to final draft

1.4 The major changes from the CSLF TRM 2013

A major change from the CSLF TRM version is a new time horizon for medium- and long-term recommendations and targets, which are now 2025 and 2035 compared with the earlier 2030 and 2050. The short- and mid-term time horizon is still 2020. The change in the medium- and long-term horizon and the fact that the short-term horizon is still kept, despite slow progress from 2013 to 2017, emphasise that CSLF TG see a need for accelerated implementation of CCS.

Other changes are mainly found in the chapters on capture (3.1) and transport and infrastructure (3.2). For capture the needs and recommendations from 2013 are still valid, but the chapter has less detailed descriptions of technology types and fundamentals and has more emphasis on industrial CCS and CCS applied to biomass and hydrogen production, as well as on learnings from large scale projects. The section on transport and infrastructure has been expanded, with emphasis on development of clusters and hubs. For storage, the risk elements and needs are essentially still valid.

1.5 CCS vs. CCUS and CCU

Carbon Capture and Storage, CCS, is used when the CO_2 is captured, transported to a storage site for permanent storage. Carbon Capture, Utilisation and Storage, CCUS, is used when the CO_2 is utilized before being stored permanently in a climate change perspective. CCU is used when the CO_2 is stored only temporarily..

A CSLF report (CSLF, 2012) divides CO_2 utilisation options into three categories:

1. Hydrocarbon resource recovery: Applications where CO_2 is used to enhance the production of hydrocarbon resources (such as CO_2-Enhanced Oil Recovery, or CO_2-EOR). This may partly offset the initial cost of CCS and contribute to bridging a gap for the implementation of long-term CO_2 storage in other geological storage media such as deep saline formations.
2. Consumptive applications: These applications involve the formation of minerals, or long-lived compounds from CO_2, which results in carbon sequestration by '*locking-up'* carbon.
3. Reuse (non-consumptive) applications: Applications where CO_2 is not consumed directly, but re- used or used only once while generating some additional benefit (compared to sequestering the CO_2 stream following its separation). Examples are urea, algal fuel or greenhouse utilisation.

In this TRM CCUS will be used for 1 and 2 above, whereas CCU applies to point 3.

CCU and particularly CCUS, are seen as a means of supporting the early deployment of CCS in certain circumstances and accelerating technology deployment.

For a CO_2-usage technology to qualify for reduction of CO_2 emissions in e.g. in trading and credit schemes, it should be required that a n*et amount of* CO_2 is eventually securely and permanently prevented from re-entering the atmosphere. However, emissions can also be reduced without CO_2 being permanently

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[6] IEA Greenhouse Gas R&D Programme

stored, by the substitution of CO_2 produced for a particular purpose with CO_2 captured from a power or industrial plant, as in, e.g., greenhouses in the Netherlands, where natural gas is burned to increase the CO_2.

2. The importance of deploying CCS

2.1. Background – the need to reduce CO_2 emissions

In 2013 total global emissions of CO_2 amounted to approximately 35.7 Gt CO_2/yr (Olivier et al., 2016), of which 8.9 Gt CO_2/yr were direct emissions from industrial processes and use of fossil fuel for heat and power in non-power industries (IEA, 2016a). To reach the COP21 2°C target IEA (2016a) estimated that energy and process related CO_2 emissions must be reduced by almost 60% in 2050 compared to 2013. It laid out a possible pathway in which the emissions trajectory will have a 50% chance of achieving the 2°C target, a scenario called 2DS (two-degree scenario).

To reach the significantly more ambitious target of 1.5°C temperature increase from anthropogenic greenhouse gas emissions the IEA (2016b) indicated that CO_2 emissions may need to fall to net-zero by the late 2030s unless global energy-related CO_2 emissions turn net-negative at some later point, and to net-zero around 2060 if negative emissions can be obtained thereafter; however, this scenario is relatively new and the uncertainties are significant.

2.2 The importance of CCS, the industry sector and negative emissions

The IEA (2016a) found that CCS may account for 12% of the accumulated reduction of CO_2 emissions in the 2DS by 2050. Benoit (2016) and IEA (2016a, b) predicted that major cuts must be made in most societal sectors in addition to the power sector. Despite an assumption that 3 Gt CO_2/yr will be captured and stored in the industry sector by 2050, the sector will still be the major contributor to accumulated CO_2 emissions between 2015 and 2050, and the largest CO_2 emission source in 2050. CCS is already happening in industries like natural gas processing, fertilizer production, hydrogen production, coal gasification and iron and steel production (GCCSI, 2016a). In addition, Japan has installed a demonstration CO_2 capture unit on a waste incineration plant (Toshiba, 2016). Benoit (2016) stated that industrial CCS will be a critical technology for many emissions intensive industries, in particular if the COP21 countries want to pursue efforts to limit anthropogenic temperature increase to 1.5°C.

Furthermore, it is likely that the concept of "negative emissions technologies" (or NETs) will need to be put into practice. In theory, 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 and challenges. Included among them are afforestation, direct air capture, and bio-CCS (or BECCS), i.e. CCS applied to conversion of biomass into final energy products or chemicals.

The importance and potential of CCS has recently been illustrated by at least three announcements:

- A white paper prepared for the June 2016 Clean Energy Ministerial and Mission Innovation (MI)[7] Ministerial emphasized the need for industrial CCS and bio-CCS (CSLF, 2016). 16 of the 21 MI members listed CCS as a core technology within their individual baseline plans
- The World Resources Institute (WRI) supported a wide spread implementation of CCS (WRI, 2016)
- The Oil and Gas Climate Initiative (OGCI) announced one billion US$ for climate investments (OGCI, 2016), of which a significant proportion of this fund will be available for CCS projects (CCSA[8], 2016).

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[7] At COP21 in Paris 2015 twenty countries plus the European Union joined Mission Innovation (MI) and pledged to double clean energy R&D funding in 5 years.

[8] Carbon Capture & Storage Association, UK

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"* and *"the scale-up of projects using these technologies over the next decade is critical. CCS could account for up to 20% of cumulative CO_2 reductions in the 2DS by 2050. This requires rapid deployment of CCS and this is a significant challenge since there are no large-scale CCS demonstrations in power generation and few in industry"* (IEA, 2012).

Despite the fact that several large scale CCS projects have come into operation since 2012 (see GCCSI 2015a, 2016b; IEA, 2016c; and Chapter 3 for details) and that the estimated contribution from CCS by 2050 has been reduced to 12 %, the IEA (2016a, c) still called for increased efforts in implementing CCS by stating that "*Moderate progress in CCS was made in 2015. Significant investment in projects and technology development by industry and governments are needed to get CCS on track to meet the 2025 target of 541 million tonnes of carbon dioxide (CO_2) stored per year* " (IEA, 2016a). The IEA saw the need for more proposals for new CCS projects, investments in CO_2 storage and continued RD&D in the field.

The IEA was supported by the GCCSI, who in its annual status on Carbon Capture and Storage (CCS) 2015 (GCCSI, 2015a) found that *"While CCS has made great progress this decade, it is abundantly clear that we must sharply accelerate its deployment."* Furthermore, key findings of GCCSI (2015a), may be summarized as follows:

- CCS is vital to meet climate goals
- Only CCS can reduce industrial CO_2 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 level
- Excluding CCS will double the cost of mitigation.

The more recent summary report from GCCSI (2016b) reinforced these statements by referring to the fact that CCS projects in operations and under construction by 2016 will capture about 40 Mt CO_2/yr, whereas roughly 500 Mt CO_2/yr must be captured and stored by 2025, 2730 Mt CO_2/yr by 2035 and more than 6000 Mt CO_2/yr by 2050 in the 2DS (IEA, 2016a), see Figure 2.1. A rough integration shows that the accumulated captured and stored CO_2 will have to be approximately 2000 Mt CO_2 by 2025 and 20000 Mt CO_2 by 2035. By 2050 the accumulated captured and stored CO_2 will have to be 94000 Mt CO_2, including 14000 Mt CO_2 negative emissions according to IEA (2016c).

Capturing and storing 500 Mt CO_2/yr imply that more than 450 CCS projects the size of Boundary Dam (1 Mt CO_2/yr) must come into operation between 2017 and 2025. This is hardly the time it takes to plan, engineer and construct a CCS chain. In particular, characterizing and qualifying storage sites may take a much as ten years. Despite the urgent actions needed to reach these numbers, the GCCSI (2016b) found that the momentum for deploying CCS is slowing and that renewed commitment and strengthened policy support is essential.

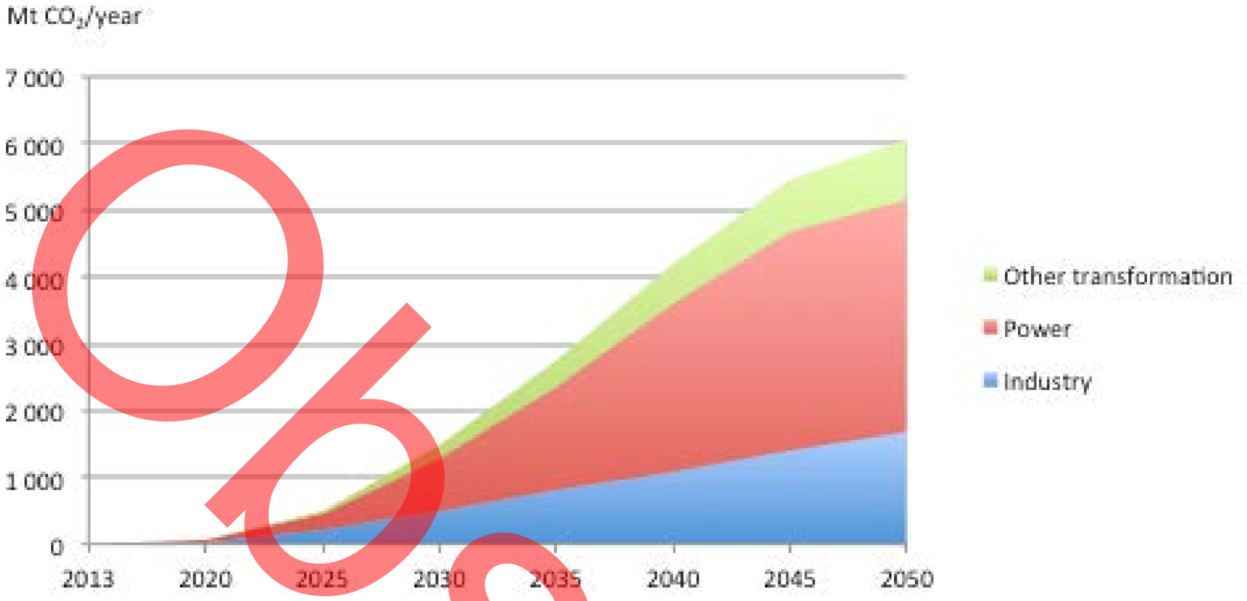

Figure 2.1. CO_2 captured and stored per year to achieve the 2DS (after IEA, 2016a)

Peters et al. (2017) developed a method based on a nested structure of key indicators to track progress towards the 'Paris goal'. They found that "many key indicators are currently broadly consistent with emission scenarios that keep temperatures below 2 °C, but the continued lack of large-scale carbon capture and storage threatens 2030 targets and the longer-term Paris ambition of net-zero emissions".

Thus, although CCS will be needed in many sectors if the COP21 targets are to be achieved, CCS is not accelerating at the pace needed to meet the ambitions of the Paris Agreement and to play the role that for example the IEA (2012, 2016a) has stated it should have. Some reasons for the slow implementation are:

- Lack of business cases and models
- Lack of political and economic incentives
- High costs, due to extra equipment (CAPEX) and operational and maintenance expenses (OPEX)
- For industrial and bio-CCS in particular; limited experience on best suited technologies
- Opposition to, or limited or absence of understanding and support, of the technology in the general public.

This TRM will deal only with technology measures that that are relevant for these points. Below is a short description of some non-technical measures needed to increase the pace of CCS implementation.

2.4. Non-technical measures needed to accelerate the pace of CCS deployment

The CSLF Charter as quoted in Section 1.1, clearly expresses a commitment to facilitate CCUS as a tool to combat climate change and as a contribution to achieve the COP21 targets. Technical as well as non-technical measures are needed to speed up the deployment of CCS as mitigating tool for global warming. The non-technical measures are not part of this TRM. They include but are not limited to:

- Developing supportive policy incentives, including equitable considerations, recognition and support for CCS on similar terms as other low-carbon technologies
- Developing markets and business models for CCS support

- Speeding up legal and regulatory frameworks for CCS, also on a regional scale (e.g. the London Protocol for transborder movement of CO_2 when considered as waste)
- Developing strategic hubs, in particular for industrial CCS, and CO_2 transportation and storage infrastructures
- Improving CCS public outreach and education, aimed at amongst other, building trust, reducing and tackling misconceptions, and supporting educators as well as community proponents of CCS projects (see also GCCSI, 2016b).

Other non-technical steps to support the implementation of CCS can be found in CCSA (2013). Although written for the UK the steps also have international relevance.

For bio-CCS non-technical issues that fall outside the scope of this TRM include:

- Lack of regulations to account for negative emissions in several jurisdictions
- Significant span in the estimates of potential scale of bio-CCS, resulting from limited understanding of the implications of and interactions between water and land use, food production, total energy use and GHG emissions, the climate system, as well as biodiversity and ecosystems
- Health and social implications, particularly in relation to other emissions and discharges, like particular matter (PM), may lead to increased negative impacts unless precautions are taken (Kemper, 2015)
- Stimulating bioenergy stakeholders for considering CCS in the sector, through targeted incentives and a non-penalising accounting methodology.

Since the 2013 CSLF Roadmap there have been developments in the application of regulations in terms of projects applying for permits, and in reviews of regulation such the EU CCS Directive. Such activities are most useful to ‘test’ the regulatory regimes. Storage permits have been successfully awarded to projects in the US, Canada, the Netherlands, Norway and the UK. The EU CCS Directive was reviewed in 2014 and found ‘fit for purpose’ and no amendments were required.

A major development not covered in the 2013 CSLF Roadmap was the inclusion of CCS into the Clean Development Mechanism (CDM) under the UNFCCC’s Kyoto Protocol. In 2011 a new set of rules specific for CCS were developed and adopted which allows CCS to be a legitimate project activity under the CDM for developing countries to use. 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 still exists much work to do. Many countries that have expressed an interest in using CCS to reduce emissions have yet to develop regulatory frameworks, notably South Africa and Mexico, while in others, regulatory frameworks remain untested.

One issue, as highlighted in the US, is the successful merging of oil production and CO_2 storage through enhanced oil recovery (CO_2-EOR). Projects employing CO_2-EOR, particularly in the US, Canada and 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 recognised for storing CO_2, transitional regulatory arrangements will need to be considered to require operators to address storage-focused performance objectives. ISO TC265 is working on this issue (see below).

Similarly, transboundary projects remain an issue. For those jurisdictions without suitable storage options, this will be an important issue. The London Protocol has its transboundary 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 lifecycle 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 operators liabilities practically limited (via transfers, indemnifications, etc.).

There is a considerable activity underway in the International Standards Organisation that could support future harmonization of regulations for geologic storage. In 2012, an ISO Technical Committee (TC) on CCS was created based on a proposal from the Standards Council of Canada, where a standard for geological storage of CO_2 (CSA Z741-12) had been released in 2012. ISO TC 265 has established six working groups, on capture, transport, storage, quantification, cross-cutting issues, and CO_2-EOR, with the intention of developing a range of different standards.

More information on recent regulatory developments can be found in Dixon, et al. (2015).

3. Technology needs

3.1 Capture

The objective of Chapter 3.1 is to identify technology needs for CO_2 capture from point sources (for example > 0.1 $MtCO_2$/yr) in the power sector, the process industry, bio-CCS as well as for other sectors. It starts with a brief assessment of the present situation. For an extensive review of CO_2 capture technologies in the power and industrial sectors, see e.g. GCCSI (2016d), ISO (2016a), and ZEP[9] (2017).

3.1.1 Power

Some power projects have become operational since the issue of the 2013 CSLF TRM, including Boundary Dam (Canada; power and post-combustion with absorption), Petra Nova (United States; power and post-combustion with absorption) and Southern Company's Kemper County (United States; power and pre-combustion with absorption). Also, several demonstration plants have been operating for many years, including Plant Barry (United States; power and post-combustion with absorption), Boreyong (power and post-combustion with a solvent) and Hadong in Korea (power and post-combustion with sorbent). Other dedicated test facilities for the capture of CO_2 have been established (but some are not operating at present) in, for example, Australia, Canada, China, Norway, the UK, France, Spain and the USA. The scale of these is generally up to 20-30MW_{th}, or a capture capacity of up to a few hundred thousand tonnes of CO_2/yr. 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 some as part of the commercial process (GCCSI, 2016a). These are found in natural gas sweetening, refineries, fertiliser production and coal gasification. Several such plants have implemented CCS, including the full-scale industry projects Quest (Shell Canada; hydrogen production, pre-combustion with absorption), the Air products Port Arthur CCS project (hydrogen production using sorbent pressure swing) and the Emirates Steel Industry (United Arab Emirates, UAE; amine based CO_2 capture from the direct reduced iron (DRI) process). In Japan, CCS on the Tomakomai refinery (GCCSI, 2016c) and the first application of CO_2 capture to waste incineration (Toshiba, 2016) both started in spring 2016. There are also activities for application of CCS to a cement plant in Norway, for example Svalestuen et al. (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 (for

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[9] The European Zero Emission Platform

example UNIDO[10], 2010; IEA/UNIDO, 2011; ZEP, 2013a, 2015a, 2017; ISO[11], 2016a; DECC, 2014, 2015; IEAGHG, 2013; Norwegian Ministry of Petroleum and Energy (MPE) 2016; GCCSI, 2016d). Findings from the studies include:

- Some currently available technologies, in particular amine solvents, can and are likely to be applied in early projects in several industries but also oxy-combustion is a candidate in some industries
- Local site conditions may favour other technologies than amine solvents, e.g. carbonate looping for 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 UK 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 employing CCS. In a road map towards zero emissions by 2050 the Norwegian process industries indicated that CCS can be responsible for 36 % of the needed 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:

- Understanding the impact of different compositions of the feed and/or flue gases compared to the power sector
- Increased operational complexity and risks
- New applications of existing technologies which are not yet proven at scale
- Plant integration risks (hidden costs of additional downtime, alternative product supplies, technology lock-in; will be site-specific)
- High costs and levels of uncertainty regarding costs.

3.1.3 Bio-CCS

Biomass absorbs carbon from the atmosphere as it grows. If the CO_2 released when biomass is converted to chemicals or energy products is captured and stored permanently in geological formations the result is net removal of CO_2 from the atmosphere or "negative emissions", provided the biomass growth is sustainable. The IPCC (2014) highlighted the importance of bio-CCS. There are currently six bio-CCS projects in operation that capture 0.1-0.3 Mt CO_2/yr, all having an ethanol plant as the source of CO_2 of biogenic origin (Kemper, 2015; ZEP, 2015b; Ensus, 2016). Three of the plants sell the CO_2 for EOR[12], one stores the CO_2 in a gas reservoir and the rest sell the CO_2 for use in the greenhouse and food industries.

The operational bio-CCS plants have a scale orders of magnitudes less than what will be needed for bio-CCS to become a major contribution to negative CO_2 emissions, although one plant (the Illinois Industrial Project, by Archer Daniels Midland Company, USA) will be upgraded to 1 Mt CO_2/yr in 2017. Estimates of the theoretical potential of bio-CCS to remove CO_2 from the atmosphere show significant spread (for example Kemper, 2015; Williamson, 2015). The scale will be limited by factors that include available biomass, competition with food production, other uses of land and water, and other end users of biomass. Potential impacts on biodiversity and ecosystems have also been identified as issues. Kemper (2015) gives a review of the benefits, impacts and challenges related to bio-CCS, and Mander et al (2016) reflect on the role of bio-CCS in a whole system perspective.

The CO_2 capture technologies for bio-CCS are basically the same as for power and heat generation and the

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[10] United Nations Industrial Development Organization
[11] International Organization for Standardization
[12] Enhanced Oil Recovery

process industry. Areas for further RD&D related to bio-CCS capture technology include (but are not limited to):

- 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
- Finding the optimal size of capture and/or conversion installations for biomass conversion and combustion
- Investment and operational costs of bio-CCS systems
- Impact of biomass, including co-firing with fossil fuels, in oxy-combustion systems, including aspects such as recirculation of CO_2 and CO_2 purification required in those systems.
- Purification of CO_2 in bio-ethanol plants.

Non-technical issues with bio-CCS fall outside the scope of this TRM. Some of these were described in Section 2.4.

3.1.4 Other sectors

Large-scale hydrogen production with CCS

Fossil fuels are used for transportation, industry and household heating and cooking around the world. This results in millions of small emission sources from which CO_2 capture will be impractical. Many of these uses of fossil fuels could be replaced by hydrogen produced from gas, oil, coal, or biomass, or also in combination with renewable energy sources, in large-scale plants and distributed through existing infrastructure. The CO_2 generated in the process can be captured (by pre-combustion capture technologies) and stored. There are no technical barriers to large-scale hydrogen production but will need to:

- Improve understanding of the possibilities and limitations of existing infrastructure for transportation and use of hydrogen or hydrogen enriched natural gas, including safety aspects
- Investigate options for:
  - Process intensification, i.e. more compact, efficient and economic solutions
  - Process integration in 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
- Develop emerging capture technologies such as membranes with potential for both catalytic reforming of the fuel and separation of H_2 and CO_2, as a more compact and economic technology
- Improve understanding of environmental and climate related benefits and trade-offs when H_2 replaces fossil fuels, including LCA[13] and total carbon footprint for options of H_2 production and use, for example, large scale production with transport to users and inter-seasonal storage *versus* local production.

For more, see for example Voldsund et al. (2016).

3.1.5 Addressing technology needs

Costs for CO_2 capture can be reduced through:

a) Applying experiences and learnings from successful, as well as unsuccessful, projects to support

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[13] Life Cycle Assessment

research, development and demonstration (RD&D) and further evolving existing CO_2 capture technologies

b) Supporting RD&D that brings out novel technologies

c) Partial capture, i.e. capture rates below the presently common target of 85-90 %. Unless costs are brought down the alternative to capturing 85 % or more of the emitted CO_2 may be no capture at all. Note, however, that this approach may be best suited in early days and that it may eventually be necessary to capture 100%

d) Combinations between CCS and renewable energy (wind, solar, geothermal, hydropower or other renewables) to supply the energy for the capture process, providing pathways towards lower costs and possibly zero or negative emissions if combined with biomass.

Learning from experience

Cost reductions for CO_2 capture are expected to come from knowledge transfer regarding planning, design, manufacturing, integration, and scale-up. The knowledge gained at scale can give important input to achieve reduced CAPEX and OPEX and provide increased confidence for deployment. First-of-a-kind technologies will offer experience on the integration between the capture unit and the power or industrial plant and can give lessons on how engineering, technical and environmental performance and even manufacturing can be improved, provided the facilities are well monitored. Data and experience should be gathered in a systematic way and engineers and researchers must be given access to the information and allowed to work on it. The data collected at the plants will be instrumental in validating and improving simulation tools that help increasing the understanding of the process and help bringing costs down.

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 applications mentioned above. However, differences in level of implementation, experiences and in maturity of application may necessitate. special considerations for each application. A network for knowledge sharing among full-scale facilities (e.g. by expanding the existing International CO_2 Test Centre Network (ITCN)[14]) would be helpful 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, including experience from the integration of CO_2 capture systems in power or industrial plants, in heat integration and other environmental control systems (SOx, NOx, H_2S), and experience in part-load operations and daily cycling flexibility, as well as experiences from the impacts of CO_2 composition and impurities. The data collected at the plants will be instrumental in validating and improving simulation, thus increasing the understanding of the process and help bringing costs down. It will benefit all parties if engineers and researchers are given access to the information[15].

A significant barrier to achieving open exchange of information, knowledge and experience is Intellectual Property Rights. Commercial entities have need to make a return on what is a significant investment, and may not want to give their intellectual property away cheaply. Confidentiality agreements may have to be considered. Alternatively, knowledge sharing can be limited to non-proprietary and generic data, such as heat integration, heat exchanger, other utilities, environmental issues, flow and process simulations, material research and fabrication, that the research and engineering communities can work on to bring costs down. The technology owners will work to improve the proprietary parts. For this, they will need to see a market.

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[14] ITCN, established in 2013, has nine members from seven CSLF nations, is a network where the focus has been (and will continue to be) on post-combustion using solvents. The CO_2 Technology Centre Mongstad (TCM) is the largest of the member facilities, with a size of 100 kt CO_2/year, which is on the border between pilot and demonstration. The other members are smaller but they all give useful experience with 2nd generation post-combustion technologies.

[15] Such a network has already been established for storage. The CO_2 Storage Data Consortium (CSDC) 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

Novel/emerging/innovative/transformative technologies

Capture technologies for the power sector, as well as for the industrial sector, are continuously in development, both with regard to improvements of currently available commercial technologies, which may be termed 2nd 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 to large pilots at 20-30MW, or a capture capacity of up to a few hundred thousand tonnes of CO_2/yr. Reviews of such technologies, including discussions on maturity in terms of technology readiness levels (TRL) can be found in Abanades et al. (2015), IEAGHG (2014) and ZEP (2017). The first two, as well as other papers, were reviewed in CSLF (2015).

Further development of currently available, as well as novel, capture technologies, including radically new approaches, will benefit from:

- Stronger modularization of the capture units, which will make them more adaptable to a range of applications, capture rates and sizes
- Improvements and more verification data for advanced computational tools
- Advanced manufacturing techniques such as 3-D printing, which have the potential to revolutionize the synthesis and functionality of advanced technologies 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 re-generation energy (strong reductions in electricity output penalty) (may have limited effect in the power sector, as we are already at 2-3 times the thermodynamic limit using “current” post-combustion technology (Rochelle, 2009))
- Solvents and sorbents with reduced degradation
- Reduced reaction time for and environmental impacts of solvents (for amine-based technologies significant improvements have been made regarding degradation and emissions)
- Improved membranes for separation of CO_2 in post- and pre-combustion capture technologies
- Oxygen carrier materials for chemical looping air separation and combustion technologies
- Parametric design to allow scaling from the large pilot scale to commercial applications.

Development on novel capture technologies benefits from international cooperation and access for researchers to top quality research facilities. A consortium of European R&D facilities has been established towards this end, the ECCSEL[16] consortium. However, the members of ECCSEL 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 post-combustion 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 and supplier as well as 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, are critical to the proper assessment of CCS performance and costs. Standardization is often lacking in CCS cost studies. ISO has issued an international standard on performance evaluation methods for post-combustion CO_2 capture integrated with a power plant (ISO, 2017. Committee draft as of Jan. 2017). In a longer time perspective this could be followed up by other standards once technologies have matured and have been implemented.

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[16] European Carbon Dioxide Capture and Storage Laboratory Infrastructure. http://www.eccsel.org

3.1.6 Recommendations CO_2 Capture

Towards 2020:
Governments and industry should work together to:

- Reduce the CAPEX and non-fuel OPEX of 2016 commercial CO_2 capture technologies for power and industry by at least 30%, while at the same time minimise environmental impacts
- Develop commercial models for integrated industrial and power CCS plants within industrial regions
- Establish a network for knowledge sharing among full-scale facilities (e.g. by expanding the existing International CO_2 Test Centre Network (ITCN) to share knowledge and experiences and increase understanding of the scale-up challenge.
- Gain experience in the integration of power plants with CCS into electricity grids that utilise renewable energy sources, seeking to develop optimal hybrid concepts with zero or negative emissions
- Resolve issues regarding industrial CO_2 capture and bio-CCS and further develop technologies for applications and implementation in pilot-plants and demonstrations
- Identify specific cases to demonstrate and validate CO_2 capture technologies suited for a range of industrial processes and bio-CCS
- Increase possibilities for pilot testing by facilitating planning and construction of pilot-scale test facilities for technologies other than solvent-based post-combustion in an internationally burden-sharing scheme
- Fund and encourage RD&D activities for new and promising 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 timeframe.

Towards 2025:
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 have CAPEX and non-fuel OPEX at least 40% below that of 2016 commercial technologies, while at the same time minimise environmental impacts.
- Implement the first full-scale CCS chains in power, industrial, and bio-CCS. These should be focused in industrial regions that have the potential to share infrastructure, rather than focused on individual projects.
- Fund promising technology ideas to be tested and verified at pilot scale (MW_{th} range and/or separating 10 to 100 kt CO_2/yr).

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)[17] of the CO_2 and at the same time achieve 50% reduction of CAPEX and non-fuel OPEX compared to 2016 commercial technologies, while at the same time minimise environmental impacts.
- Continue progressive roll out and expansion of full-scale CCS chains and clusters in power, industrial, and bio-CCS.

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[17] Target capture rates will need to address the topic of residual emissions, as most capture technology developers and users design for optimal rates of 85 – 90% capture. A study by IEAGHG (2016) concluded that these residual emissions were "likely to be really important in determining the extent of the role for fossil fuels with CCS especially in extremely emissions-constrained global scenarios".

3.2 CO_2 Infrastructure

Coping with the large volumes of CO_2 to be collected from future power plants and industrial clusters[18], 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[19] and common transport to a common storage reservoir. This section will deal with the transport part and collection hubs.

NOTE: A barrier to the roll out of international infrastructure for CCS is the London Protocol's prohibition on export of waste, which currently means that CO_2 cannot be exported for storage across borders. An amendment to change this is in place but not in force due to a very slow rate of ratification. CO_2 exported for use in CO_2-EOR is not prohibited by this export clause.

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. GCCSI (2016d) and ZEP (2017) give overviews of transport of CO_2 by pipelines and ships, the former also of RD&D activities.

Pipelines are the most common method for transporting the large quantities of CO_2 involved in CCS projects. In USA around 7600 km of onshore pipelines transport roughly 68 million tonnes of CO_2/yr (DOE NETL, 2015; GCCSI, 2016d). 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 modelling capabilities of properties and the behaviour of CO_2 streams, validated flow assurance tools for CO_2 rich mixtures, the impact of impurities on compression work and on pipeline materials (seals, valves etc) and corrosion, phase equilibria, and equations-of-state of complex CO_2 mixtures, as well as possible repository requirements (Munkejord et al, 2016). Other RD&D needs are 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. Other technology needs include effective and accepted safety measures for large supercritical pipelines, particularly in more populated areas, as has been experienced by the Barendrecht project in the Netherlands, although the opposition to that project was not only caused by the CO_2 pipeline (Feenstra et al., 2010). This is particularly important for clusters and plants with several units, as these will have much higher capacities than point-to-point projects. Public outreach and stakeholder dialogue and communication will be important.

Finally, there are currently no commonly agreed specifications for the CO_2 quality 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 that do not give unmanageable corrosion and lead to safe transport and injection are identified and documented for each case.

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[18] Here a cluster is a geographic concentration of emission sources

[19] Here a hub is a facility that collects captured CO2 from several sources of collective size (e.g. > 10 kt CO_2/yr)

Ship transport can be an alternative to pipelines in a number of regions of the world, 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 (1000-2000 m^3). The CO_2 is transported as a liquid at 15–18 bar and -22 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 Mærsk Tankers (undated), Anthony Veder (Vermeulen, 2011)) and Chiyoda (2011, 2012) have initiated preliminary design. A feasibility study for implementation of a full-scale industrial CCS project in Norway concluded that ship transport is not a technical barrier for realization of the full-scale project and that ship transport of CO_2 can be an enabler for realizing full-scale CCS in the country (MPE, 2016; Økland, 2016). This is in agreement with a major Dutch study (CATO, 2016), a Scottish literature study (Brownsort, 2015) and the study for Antony Veder (Vermeulen, 2011). The studies considered ships in the range of 5 kt to 50 kt CO_2 capacity. The MPE study also included 45 bar and +10°C in addition to the two above mentioned conditions.

The Norwegian feasibility studies did not identify major issues with loading and off-loading 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 the part most in need of further engineering for optimisation. Other needs for technology development of ship transport are linked to optimization and qualification of the first systems for large-scale projects.

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

Transport of smaller volumes of industrial and food grade CO_2 has been 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, 2015b). Roussanaly et al, (2017) show that train-based transport of CO_2 may have site specific cost benefits; in their situation 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, the integration of different capture systems and CO_2 compositions, the scale-up risks, solutions for intermediate storage as well as seaborne or land transport, 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 IEAGHG (2015) made an in-depth review of 12 cluster and hub locations, of which three are in operation - Denver City, Gulf Coast and Rocky Mountain hubs, all in USA. These three 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 UK) and the United Arab Emirates. Systems like Teesside (Tees Valley), UK, and ROAD, the Netherlands, are well advanced and can offer experience in the design of new systems. The Alberta Carbon Trunk Line (ACTL), Canada, is under construction. In Europe, several studies have identified CCS hubs or infrastructures, for example ZEP (213b; 2016), Jakobsen et al (2016), Bellona (2016) and Brownsort et al. (2016), the last by re-use of an existing pipeline.

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

The United Kingdom (UK) CCS Cost Reduction Task Force (CCSA, 2013) found that CO_2 transport costs could be reduced by 50 per cent with the deployment of large, efficiently utilised pipelines, 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, moderate impact on the total cost of a CCS chain, particularly for onshore pipelines (IEAGHG, 2015), although the cost may be significant in absolute money terms (Roussanaly et al., 2014). However, there are other benefits in addition to cost sharing (GCCSI, 2016e; ZEP, 2013b; IEAGHG, 2015), including:

- Lowering costs by utilising benefits of connecting low-cost industrial sources with storage sites in building early infrastructure, into which more costly CCS projects can tie
- Lowering investments in transportation systems for the first CCS projects
- Lowering the entry barriers for participating CCS projects, such as:
    - emitters with small volume sources
    - emitters with limited or no access to local storage
    - industrial sources that will have to utilise CCS
- 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
- Minimising the environmental impacts associated with infrastructure development, as well as the impact on communities
- Minimising and streamlining efforts in relation to planning and regulatory approvals, negotiations with landowners and public consultations
- Sharing and utilising 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) and the IEAGHG (2015) 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 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 have started that include the separation of CO_2 capture at the sources from the transport and storage parts (Esposito et al., 2011; MPE, 2016; Pöyry, Teesside Collective, 2017 and Banks et al., 2017). In these models a split of costs and risk between the government and the industry players have been explored, e.g. that governments take a certain responsibility to develop transport and storage networks. These issues, as well as the London Protocol, are outside the scope of the CSLF TRM.

3.2.3 Recommendations CO_2 Infrastructure

Towards 2020:
Governments and industry should work together to:

- Acquire thermodynamic data for, and understand the effects of, impurities on the thermo-physical properties of CO_2 streams, on pipeline materials (fracture control), on cross-chemical reactions forming acids and elemental sulphur in the CO_2 stream, and on formation of corrosive phases and solid products
- 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
- Start the identification, characterization and qualification of CO_2 storage sites for the large-scale systems
- Identify business cases for transportation and storage companies.

Towards 2025:
Governments and industry should work together to:

- Set out to design and initiate large-scale CO_2 networks that integrate capture, transport and storage, including matching of sources and sinks
- Implement initial shared infrastructure for a limited number of plants within industrial clusters. This should recognise 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:

- Expand and roll out 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.

The GCCSI (undated) currently identifies five large-scale operating “pure” geological storage projects in the world that are operational or will become operational in 2017: Sleipner CO2 Storage Project (Norway – 0.9 Mtpa), In Salah CO2 Storage Project (Algeria – currently suspended), Snøhvit CO2 Storage Project (Norway – 0.7 Mtpa), Quest (Canada – 1.0 Mtpa), Illinois Industrial CCS Project (USA – 1.0 Mtpa) and, most likely be the end of 2017, Gorgon CO_2 Injection Project (Australia – 3.4 Mtpa). The first two are offshore projects while the last three are located onshore.

The GCCSI identifies a further 8 “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 now been running for 20 years without any incidents, and has successfully stored more than 16 million tons of CO_2 injected into the Utsira Formation in the Norwegian Sector of the North Sea, thus demonstrating that we can safely and securely store CO_2 in significant quantities over decades.

At Snøhvit, in the Barents Sea, CO_2 from an onshore LNG plant is transported offshore using a 150 km long pipeline and injected via a sub-sea template into neighbouring reservoirs from where natural gas is produced from a depth of about 2400 m.

Shell’s Quest CCS Project in Alberta, Canada, commenced operations in 2015. It is capturing and storing more than 1 mtpa.

The Illinois Industrial CCS Project is the first CCS project in the United States to inject CO_2 into a deep saline formation at about 1 mtpa, and 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 Project in Australia commenced operations in 2017 with injection of CO_2 below Barrow Island, off the northwest coast of Australia, at a rate of 3.4-4.0 mtpa for at least 30 years.

The Norwegian Government (2016) aims to build a full scale CCS chain by 2022, and a feasibility study conducted during 2016 identified three possible industry sources of CO_2 (providing in total 1.3 million tons CO_2/yr) and a preferred storage site located 50 km from the coast.

The continued deployment of industry-scale projects is essential for the accelerated technology development needed to reduce cost and enhance confidence in CO_2 storage as a safe and permanent solution for curbing CO_2 emissions. 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. In the planned Norwegian CCS project, the state takes on responsibility for funding the transport and storage infrastructure together with the 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.

Identification of suitable storage sites and validation of storage capacity remains a challenge especially where geological and geophysical data coverage is sparse. However, based on evaluations of storage capacities, for example in the United Kingdom and Norway, it is anticipated that sufficient storage is available for more than 50 years. For instance, the Norwegian CO_2 storage atlas indicates a capacity on the Norwegian shelf of 80 billion tons CO_2, which is 1000 years of total Norwegian emissions. (For comparison, the global CO_2 emissions per year from industry and power was 35.7 billion tons in 2014).

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 will be a key to establishing confidence.

3.3.1 Identified technology needs

The 2013 Technical Roadmap highlighted the risk management elements where continued research is required, and these essentially remain valid today, although significant progress is being made. It is widely accepted that a retention of 99% over 1000 years is sufficient from a climate perspective.

- Storage
    - Demonstration of methods and protocols for the characterization of proposed CO_2 storage sites that will convince regulatory agencies and the public that storage is secure and safe.
    - Development of a unified approach to estimating CO_2 storage capacity.
- Monitoring
    - Development, demonstration and validation of new and more accurate monitoring technologies, and commercialization and cost-optimization of existing monitoring technologies and techniques to support the risk management of storage.
    - On-line methods that enable monitoring over large areas are investigated, including the challenge of handling large volumes of data.
- Advance understanding of long-term reservoir behaviour.
    - Improvement of the understanding and modelling of fundamental reservoir and overburden processes, including hydrodynamic, thermal, mechanical and chemical processes.

  - Development of improved and fit-for-purpose well and reservoir technologies and management procedures, including well integrity.
- Offshore EOR
  - Due to large well spacing in offshore fields compared with onshore EOR, methods for improved volumetric sweep are needed. Optimal well placement and mobility controls of CO_2 are instrumental for success.
  - Offshore EOR remains to be demonstrated.
- Storage integrity
  - Forecast CO_2 pressure development and related geomechanical effects to predict and prevent leakage.
  - Design and operation of robust CO_2 wells to prevent leakage.
  - Development of testing and validation of 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).
  - Improve the understanding of the effects of impurities in the CO_2 stream, including their phase behaviour, on the capacity and integrity of the CO_2 storage site, with emphasis on well facilities (overlaps with CO_2 transport).
- Storage closure, post-injection monitoring and liability transfer
  - Acquire experience with closure and post-closure procedures for CO_2 storage projects.
  - Subsea CO_2 pipelines and legal aspects concerning national sovereignty and neighbouring 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.

An example of progress is the release of a report on the classification of injection projects by the United Nations' Expert Group on Resource Classification (UNECE[20], 2016)

Current research initiatives globally are focussed on developing low-cost fit-for-purpose monitoring and verification programs. This includes the use of fibre-optic technology for downhole observations and optimisation of the coverage and frequency of seismic surveys (that is, how often should they be conducted).

3.3.2 Recommendations Large-scale CO2 Storage

Towards 2020:
Governments and industry should work together to:

- Maintain momentum for the Large-Scale Saline Storage Project Network 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 data and knowledge, for example, in initiatives like the CO_2 Storage Data Consortium; an open, international network developing a common platform for sharing datasets from pioneering CO_2 storage projects.
- Encourage RD&D activities to close technology gaps and validate the methods/technologies in case studies to accelerate the pace of CCS deployment
- Continue work on ISO standards for geological storage of CO_2

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[20] United Nations Economic Commission for Europe

- Encourage research into the interface between transport and storage
- CSLF to support the development of national storage assessments in developing nations
- Public communication on CO_2 storage projects to increase knowledge and acceptance in general public – to gain a social licence to operate

Towards 2030:
Governments and industry should work together to:

- Permanently store 0.5 $GtCO_2$ /year by 2025 (or have permanently captured and stored 2 $GtCO_2$)
- Promote the deployment of a large-scale CO_2 storage site, 10–100 million tons CO_2 per year, for example storing CO_2 from Europe in sites in the North Sea, building on experience from current projects and pilots
- Support 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
- Promote the first offshore CO_2-EOR pilot project as part of deployment of large-scale CO_2 storage, as CO_2 becomes available in amounts and during time windows relevant for EOR.
- All CSLF member countries to have national storage assessments publicly available
- All CSLF members to identify pre-competitive (data gap identification) programs in key potential storage basins
- CSLF to develop robust conceptual workflow to assure regulators that site characterisation meets international leading practice

Towards 2035:
Governments and industry should work together to:

- Permanently store 1.5 $GtCO_2$ /year by 2035 (or have permanently captured and stored 20 $GtCO_2$)
- All CSLF member countries to have commenced regional studies of key potential storage basins

3.3.3 Recommendations Monitoring and Mitigation/Remediation

Towards 2020:

- Cost-optimisation of existing monitoring technologies and techniques, and development, demonstration and validation of new measuring and monitoring techniques, onshore and offshore. This includes for leakage in terms of anomaly detection, attribution and leakage quantification.
- Develop and demonstrate monitoring strategies to optimise monitoring and make monitoring more cost-efficient for large-scale projects.
- Develop mitigation and remediation methods for leakage, including well leakage, and test in small-scale, controlled settings.
- Validate remediation technologies on a large scale, including well leakage.
- Identify minimum requirements/objectives for M&V programs, both onshore and offshore, in line with legislation and regulations.

Towards 2030:

- Reduce monitoring and verification (M&V) costs by 25% from 2015 levels

Towards 2035:

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

3.3.4 Recommendations Understanding the Storage Reservoirs

- Further advance the simulation tools, with a focus on multiphase flow algorithms and coupling of fluid flow to geomechanical models
- Develop and agree on consistent methods for determining CO_2 storage capacity reserves at various scales (as opposed to storage resources), at various levels of project maturity, and with a global distribution of this capacity (important for policymakers)
- Further improve on material (steel and cement) technologies to reduce cost and risk (such as corrosion)
- Enhance ability to predict storage efficiency more precisely 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 build-up and hydraulic fracturing
- Recommended workflow for caprock and fault integrity studies in CO_2 storage sites

3.4 Utilisation

CO_2 for EOR is the most widely used form of CO_2 utilisation, with more than 120 operations, mainly onshore in North America. In 2015 over 68 million metric tonnes of CO2 was injected in depleted oil fields in the United States for EOR. Canada has been injecting sour gas, a mixture of CO_2 and hydrogen sulphide 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 field names Lula. Many other countries including the United Kingdom, Japan, China, United States, Indonesia, Norway, and others are working to characterize the opportunities for offshore CO_2-EOR. Other specific applications for CO_2-enhanced hydrocarbon recovery include enhanced coal bed methane production (ECBM), enhanced gas recovery (EGR), enhanced gas hydrate recovery (EGHR), hydrocarbon recovery from oil shale and the fracturing of reservoirs to increase oil/gas recovery. However, these other applications are processes still being developed or tested in pilot-scale tests (CSLF; 2012, 2013).

Other potential utilisation options of CO_2 that will lead to secure long-term storage are the use of CO_2 as the heat-transfer agent in geothermal energy systems, enhanced water recovery, carbonate mineralization, concrete curing, bauxite residue and some algae cultivation that create stable products such as bio-plastics or as a replacement for animal feed. Mixing CO_2 with bauxite residue ('red mud') is being demonstrated in Australia (GCCSI, 2011). Enhanced water recovery is being demonstrated in China and has the opportunity to provide produced waters for other arid regions of the word. EWR has the ancillary benefit of optimizing storage capacity and mitigating pressure differences in the storage formations (Li et al., 2014). In addition, there are several forms of re-use of CO_2 already in use or being explored, including in urea production, ethylene oxide production, ethanol production, utilisation in greenhouses, conversion to polymers, methanol and formic acid production, and the cultivation of algae as a pathway to bio-energy animal feed, and other products. These will not lead to permanent storage but may contribute to the reduced production of CO_2 or other CO_2 emitting substances. Also, there may be other related benefits: as an example, the utilisation of waste CO_2 in greenhouses in the Netherlands already leads to a better business case for renewable heating and a rapid growth of geothermal energy use in the sector. Finally, the public opinion on CCS as a whole may become more positive when utilisation options are part of the portfolio.

For many of the utilisation options of CO_2 the total amount that can be permanently stored is, for all practical and economic purposes, limited for the moment. The lack of scalability and the economic challenges are significant barriers to the deployment of CO2 utilisation technologies in the near and long-term (NCC[21], 2016) However, in some countries utilisation provides early opportunities to catalyse the implementation of CCS. In this way, the CO_2 utilisation pathways can form niche markets and solutions as one of the routes to commercial CCS before reaching their own large-scale industrial deployment. This applies not only to oil producing countries but also to regions with evolved energy systems that will allow the implementation of feasible CO_2 business cases.

Recent reviews of utilisation of CO2 are SEAB[22] (2016);; DoE[23] (2016); NCC (2016) CSLF (2012, 2013a), GCCSI (2011), ADEME (2010), Styring (2011), Dijkstra (2012), Tomski (2012) and Markewitz et al. (2012). In April 2013 The Journal of CO2 Utilisation was launched, providing a multi-disciplinary platform for the exchange of novel research in the field of CO2 re-use pathways.

3.4.1 Identified technology needs CO_2 Utilisation

There are technical and policy reasons to further examine the technical challenges of the utilisation of CO2. The recent reviews of utilisation by NCC (2016) CSLF (2012, 2013a), GCCSI (2011) and Styring (2011) all point to several possible topics requiring RD&D, including:

- Improving the understanding of how to increase and prove the permanent storage of CO_2 in CO_2-EOR operations. 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 availability of high quality CO_2 at an economic cost, infrastructure for transporting CO2 to oil fields; and legal, regulatory and long-term liability must be addressed.
- CSLF (2017), to be published) points out that necessary efforts to make offshore CO_2-EOR economic include
    - Making sufficient CO2 must be available, e.g. by building.transport infrastucture that connects sources reservoirs
    - RD&D support to development and qualify new technologies
    - Develop business models for offshore CO_2-EOR
- Improving the understanding of how to increase and prove the permanent storage of CO_2 in EGR, ECBM, EGHR, enhanced shale gas recovery and other geological applications of CO_2.
- Developing and applying carbonation approaches (i.e. for the production of secondary construction materials).
- Developing large-scale, algae-based production of fuels and animal feed to offset primary fuel consumption and decrease agricultural cultivation practices which might have large CO2 foot print.
- Improving and extending the utilisation 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 are enable synthetic transformations based on electro or photo catalysts made from inexpensive elements and new materials using advanced manufacturing techniques to reduce over potential and increase activation sites that enable large scale processes for conversion of CO2 directly to fuels or other products..

CO_2-EOR has the largest potential of the various CO_2 utilisation options described previously, and has not been sufficiently explored to date as a long-term CO_2 storage option. So farthe CO_2-EOR Weyburn-Midale project in Canada, the CO2-EOR Project at the Bell Creek field in Montana, and the CO2-EOR project at Cranfield site in Mississippi have performed extensive monitoring and verification of CO_2 stored in EOR operations

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[21] National Coal Council
[22] Secretary of the Energy Advisory Board
[23] Department of Energy, USA

3.4.2 Recommendations CO_2 Utilisation

Towards 2020:

- Resolve technical challenges for the transition from CO_2 -EOR operations to CO_2 storage operations.
  - Conduct a review of the Subpart RR reporting requirements for CO_2 operations that are claiming credits under the 45Q tax credit in the United States to understand how these standard can be applied to global EOR project. These standards are being used by several projects in the United States to demonstrate the permanent storage of CO_2 during EOR operations.
  - 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 R&D pathways for the development of novel catalysts using abundant materials and advanced manufacturing techniques to produce nano-catalysts.
  - 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 utilisation family of technologies including life-cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 re-use pathways and the energy requirement of each technology using technological modeling.
- Address policy and regulatory issues related to CO_2 utilisation.

4. Summary

Since the last full update of the CSLF TRM in 2013, there have been advances and positive developments in CCS, although at a lower rate than is necessary to achieve earlier objectives. New Large-Scale Integrated Projects (LSIPs) as well as demonstration scale projects have come into operation both in the power and industry sector and legislation has been put in place in some jurisdictions. This CSLF TRM 2017 has been updated in light of the outcomes of the COP21v meeting in Paris in November 2015. In particular, the importance of CCS in industries other than power and the potential of achieving negative CO_2 emissions using a combination of biomass and CCS is highlighted in the CSLF TRM 2017. The importance of bringing costs down by developing industrial clusters, CCS appkied to use of biomass, and CO_2 transport and storage hubs are pointed out.

Based on reviews of several status reports on CCS and technical papers as well as on comments and input from international experts the main findings of the CSLF TRM 2017are:

- CCS works and has been implemented in power and industry
- The implementation of CCS is far behind a trajectory to reach the two degree and even less target set by COP21
- The main reasons for the slow implementation are
  - Lack of policy incentives
  - Lack of business models
  - High costs

Significant efforts are needed to reach the targets of COP21, i.e. 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. The efforts must include actions as:

- 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
- Significant efforts are needed to reach the targets of COP21, i.e. 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. The efforts must include actions as
- Facilitation of exchange of data and experiences, particularly from existing large-scale plants with CCS
- Support to continued and comprehensive RD&D
- Facilitation of clusters and hubs

5. Priority Actions Recommended for Implementation by Policy Makers

Based on the findings in this report governments should work together to:

Implementing sufficient large-scale projects in the power and industry sectors to:
- Permanently store 0.5 $GtCO_2$ /year by 2025 (or have permanently captured and stored 2 $GtCO_2$)
- Permanently store 2.7 $GtCO_2$ /year by 2035 (or have permanently captured and stored 20 $GtCO_2$))

This may be achieved through the following actions:

- Developing supportive policy incentives, including equitable considerations, recognition and support for CCS on similar terms as other low-carbon technologies
- Developing markets and business models for CCS support
- Speeding up legal and regulatory frameworks for CCS, also on a regional scale (e.g. the London Protocol for transborder movement of CO_2 when considered as waste)
- Developing strategic clusters and hubs, in particular for industrial CCS, and CO_2 transportation and storage infrastructures, including early identification and characterisation of potential storage sites
- Improving CCS public outreach and education, aimed at amongst other, building trust, reducing and tackling misconceptions, and supporting educators as well as community proponents of CCS projects
- Exchanging data from large scale projects that have been in operation
- Supporting RD&D for novel and emerging technologies along the whole CCS chain (e.g. for capture to reduce costs by 30% by 2020, 40% by 2030 and 50% by 2035)

More specific technical recommendations are:

<u>Towards 2020:</u>

Governments and industry should work together to:
- Resolve issues regarding industrial CO_2 capture and bio-CCS and further develop technologies for applications and implementation in pilot-plants and demonstrations
- Initiate planning and design of large-scale power, industrial, and bio-CCS capture plants within industrial regions with shared infrastructure that will be ready for operations by 2025

- Establish a network for knowledge sharing among full-scale facilities (e.g. by expanding the existing International CO_2 Test Centre Network (ITCN) to share knowledge and experiences and increase understanding of the scale-up challenge.
- Increase possibilities for pilot testing by facilitating planning and construction of pilot-scale test facilities for technologies other than solvent-based post-combustion in an internationally burden-sharing scheme
- Acquire necessary data for the impacts of impurities for CO_2 transport and establish and validate models that include the effects
- 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
- Start the identification, characterization and qualification of CO_2 storage sites for the large-scale systems
- Maintain momentum for the Large-Scale Saline Storage Project Network 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 data and knowledge, for example, in initiatives like the CO_2 Storage Data Consortium; an open, international network developing a common platform for sharing datasets from pioneering CO_2 storage projects.
- Further advance the simulation tools, with a focus on multiphase flow algorithms and coupling of fluid flow to geomechanical models (pressure build-up, fracturing etc)
- Enhance ability to predict storage efficiency more precisely by using experience from successful injections (e.g. Sleipner and Snøhvit), knowledge on geological complexity to improve models on reservoir injectivity and plume migration and agreed and consistent. methods for determining CO_2 storage capacity
- CSLF to support the development of national storage assessments in developing nations
- Develop, cost-optimize and demonstrate monitoring technologies and strategies
- Develop and validate mitigation and remediation methods for leakage, including well leakage, and test in small-scale, controlled settings.
- Map opportunities, conduct technology readiness assessments and resolve main barriers for the implementation of the CO_2 utilisation family of technologies including life-cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 re-use pathways and the energy requirement of each technology using technological modelling.

<u>Towards 2025:</u>
Governments and industry should work together to:

- Fund promising technology ideas to be tested and verified at pilot scale (MW_{th} range and/or separating 10 to 100 kt CO_2/yr).
- Set out to design and initiate large-scale CO_2 transport networks that integrate capture, transport and storage, including matching of sources and sinks
- Implement initial shared infrastructure for a limited number of plants within industrial clusters.
- Support 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
- Promote the deployment of a large-scale CO_2 storage site, 10–100 million tons CO_2 per year, for example storing CO_2 from Europe in sites in the North Sea, building on experience from current projects and pilots
- Promote the first offshore CO_2-EOR pilot project as part of deployment of large-scale CO_2 storage, as CO_2 becomes available in amounts and during time windows relevant for EOR.
- Reduce monitoring and verification (M&V) costs by 25% from 2015 levels

<u>Towards 2035:</u>

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)[24] of the CO_2 and at the same time achieve 50% reduction of CAPEX and non-fuel OPEX compared to 2016 commercial technologies.
- Continue progressive roll out and expansion of full-scale CCS chains and clusters in power, industrial, and bio-CCS.
- Expand and roll out large-scale CO_2 transport networks that integrate CO_2 capture, transport and storage, including matching of sources and sinks.
- Reduce M&V costs by 40% from 2015 levels

6. Follow-Up Plans

The CSLF should continue to monitor progress in light of the Priority Actions suggested below, report the findings at the Ministerial meetings and suggest adjustments and updates of the TRM. The CSLF can thus continue to be a platform for an international coordinated effort to commercialize CCS technology. IEA and IEAGHG. CSLF will need to continue working with these organizations. To this end, it is recommended that the CSLF, through its Projects Interaction and Review Team (PIRT), monitor the progress in CCS in relation to the Recommended Priority Actions.

Through the CSLF Secretariat, the PIRT will:

- Solicit input with respect to progress of CCS from all members of the CSLF,
- Gather information from a wide range of sources on the global progress of CCS, including the and collaboration partners;
- Prepare a simple reporting template that relates the progress of the Priority Actions;
- Report annually to the CSLF TG; and
- Report biennially, or as required, to the CSLF Ministerial Meetings.

The PIRT should continue to have the responsibility to prepare plans for and be responsible for future updates of the CSLF TRM.

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From Norway: Philip Ringrose, Sveinung Hagen, Jørg Aarnes, Jens Hetland, Arvid Nøttvedt, Grethe Tangen,

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[24] Target capture rates will need to address the topic of residual emissions, as most capture technology developers and users design for optimal rates of 85 – 90% capture. A study by IEAGHG (2016) concluded that these residual emissions were “likely to be really important in determining the extent of the role for fossil fuels with CCS especially in extremely emissions-constrained global scenarios".

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Abbreviations and Acronyms

[to be added]

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