MISSION INNOVATION

Accelerating the Clean Energy Revolution

Report of the Mission Innovation Carbon Capture, Utilization and Storage Experts' Workshop

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Disclaimer: This report is the product of the carbon capture, utilization, and storage (CCUS) experts' workshop held in Trondheim, Norway June 19 and 20, 2019. The content of this report reflects the views and opinions of the workshop participants and report authors and does not necessarily reflect those of their respective governments, companies, or academic institutions.

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Carbon Capture Innovation Challenge

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1. Preface

The global energy system relies heavily on the combustion of fossil fuels, which are used to produce electricity and play a critical role in the industrial sector. This pertains in particular to the manufacture of cement, fertilizer, refineries and steel. Globally, power and industry account for about 50% of all greenhouse gas (GHG) emissions. Fossil fuels are expected to play an important role in the future global energy system provided they can be used sustainably. Technical solutions are needed to reduce and remove carbon dioxide (CO_2) emissions from combustion.

Carbon capture, utilization, and storage (CCUS) is a key technological approach that can achieve this goal. CCUS is a process that includes the separation of CO_2 from power station or industrial plant effluents, to be used as a feedstock for useful products and/or permanently stored in underground geological formations. CCUS can achieve significant CO_2 reductions from power plants (fueled by coal, natural gas, and biomass) and industrial applications. Industrial applications of CCUS include upstream oil and gas production, refineries, cement production, iron and steel production, and fertilizer manufacturing. These large point sources of CO_2 emissions have few alternative options for significant reductions.

Efforts to integrate bioenergy with CCUS also represent a pathway to negative emission technologies (NET), which models suggest will become increasingly important in achieving deep decarbonisation. Such technology could capture CO_2 from, for example, the waste stream of bioenergy facilities for storage. NET's are coined Climate Positive Solutions (CPS) in this report, words can have a significant role in building confidence and acceptance for new solutions.

Achieving Paris Agreement (PA) targets will require a significant acceleration of the development and deployment of technologies that dramatically reduce the output of CO_2. CCUS developments to date are noteworthy, but additional extensive and far-reaching efforts are required to combat climate change. Globally, the total CO_2 capture capacity of the 22 current projects (in operation or construction) is about 40 million tons per annum. The IEA's Energy Technology Perspectives report released in 2016 estimates that CCUS could provide 12% of the GHG emission reductions in the power sector alone. These are efforts needed to meet a 2°C scenario by 2050, or about 3.5 gigatons of CO abatement per year. In this scenario, 6.4 gigatons of CO_2 are captured in 2050 in the power and industrial sectors combined.

Projects in power and industrial sectors have continued to demonstrate the technical feasibility of CCUS. However, overall costs need to be reduced for the technology to be adopted at a sufficient scale to meet the challenges of climate change. Adjacent to this suitable business models must be developed. This is an area which have shown good progress later years with the US Q45 and with quota price rising in Europe. Waste to energy plants also offers the possibility to use tariffs to store CO_2 from end-users. The science and technologies supporting CCUS have experienced great advances over the last decade, yet opportunities remain for reducing costs, improving performance, creating better business and regulatory models, and discovering new uses for CO_2.

The *Mission Innovation Carbon Capture Challenge* aims to provide a platform for advancing broad international collaboration in CCUS research and development that could significantly reduce CO_2 emissions. This report presents the outcome of the ***Mission Innovation CCUS Experts workshop*** **held in Trondheim, Norway in June 2019,** in which attendees worked to identify research gaps, opportunities, and priorities in CCUS. The workshop addressed six different topics, and the report presents summaries and recommendations for all six topics, in short-, medium-, and long-term perspectives.

2. Contents

3. Acronyms

45Q	refers to "section 45Q of the U.S. tax code"
ACT	Accelerating CCS Technologies
B2DS	beyond 2°C scenario
BEBCS	bioenergy-biochar systems
BECCS	bioenergy with carbon capture and storage
CA	California
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCUS	carbon capture, utilization and storage
CO2	carbon dioxide
CPS	climate positive solutions
DAC	direct air capture
deNOx	de-nitrogen oxides systems
deSOx	de-sulphurization systems
EII	energy intensive industry
EOR	enhanced oil recovery
ETP	energy technology perspective
GHG	greenhouse gas
IEA	International Energy agency
IP	intellectual property
LCA	life cycle analysis
MI	Mission Innovation
NASA	National Aeronautics and Space Administration
NDC	nationally determined contributions
O&G	oil and gas
RNG	renewable natural gas
RTS	reference technology scenario
R&D	research and development
R&I	research and innovation
SRL	storage readiness level
SRMS	storage resource management system
TCM	Technology Centre Mongstad
TEA	techno economic assessment
TRL	technology readiness level

4. Introduction

Mission Innovation (MI) is a global initiative of 24 countries and the European Commission (on behalf of the European Union) working to reinvigorate and accelerate global clean energy innovation with the objective to make clean energy widely affordable. MI was announced at COP21 on November 30, 2015, as world leaders came together in Paris to commit to ambitious efforts to combat climate change. Accelerating clean energy innovation is essential to limiting the rise in global temperatures to well below 2˚C. The global community has made remarkable progress in driving down the costs and increasing the use of key clean energy options. However, these impressive gains are still insufficient to meet our long-term climate goals while providing affordable, reliable and secure energy supplies. In support of these efforts, members launched MI in 2015 with the following goal:

> *In support of economic growth, energy access and security, and an urgent and lasting global response to climate change, our mission is to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions to provide widely affordable and reliable clean energy solutions that will revolutionize energy systems throughout the world over the next two decades and beyond.*

As part of the launch statement, members committed to:

- Seek to double their governmental and/or state-directed clean energy clean energy research, development and demonstration (RD&D) investments over five years.
- Work closely with the private sector as it increases its investment in the earlier-stage clean energy companies that emerge from government programs.
- Build and improve technology innovation roadmaps and other tools to help in our innovation efforts, to understand where RD&D is already happening, and to identify gaps and opportunities for new kinds of innovation.
- Provide, on an annual basis, transparent, easily accessible information on their respective clean energy RD&D efforts

In 2016, Mission Innovation (MI) members came together at the United Nations Conference of Parties in Morocco (COP22) to endorse seven *Innovation Challenges* (ICs). At the third MI Ministerial in 2018, members endorsed the addition of an eighth IC on Renewable and Clean Hydrogen. The ICs cover the entire spectrum of RD&D: from early-stage research needs assessments to technology demonstration projects. Each IC consists of a global network of policymakers, scientists and innovators working towards a common objective and built around a coalition of interested MI members. Through the ICs, MI members aim to encourage increased engagement from the global research community, industry, and investors, while also providing opportunities for new collaborations between MI members.

The Mission Innovation Carbon Capture Challenge aspires to provide a platform for advancing broad international collaboration in CCUS research and development that could significantly reduce CO_2 emissions from power plants and energy-intensive industries. The goal of the Carbon Capture Innovation Challenge is twofold: first, to identify and prioritize breakthrough technologies; and second, to recommend research, development, and demonstration (RD&D) pathways and collaboration mechanisms. The objective is to enable near-zero CO_2 emissions from power plants and carbon intensive industries.

In September 2017, a technical Mission Innovation CCUS workshop was hosted in Houston, Texas, by the United States. The workshop brought together 260 of the world's leading CCUS experts from academia and industry to discuss breakthrough opportunities and find international RD&D synergies in carbon capture, geologic storage, and CO_2 utilization. The MI CCUS Experts' Workshop discussed basic research and development (R&D) needs in CO_2 capture, CO_2 utilization, geologic storage, and cross-cutting CCUS topics. Experts created an international consensus on the most critical scientific challenges associated with CCUS, and they established a set of Priority Research Directions (PRDs), which have the potential to make a significant impact on CCUS technology performance. The report, which was released at the Mission Innovation CCUS Roundtable today in Malmø, Sweden at the third Mission Innovation Ministerial (MI-3), includes 30 PRDs to guide future CCUS R&D. The report, titled *Accelerating Breakthrough Innovation in Carbon Capture, Utilization, and Storage*, can be accessed here.

In June 2019, a *Mission Innovation Challenge CCUS workshop* with 135 attendees was held in Trondheim, Norway, back-to-back with the TCCS-10 Conference. The purpose was to move ahead and follow up on the important work so far, to ensure continued progress in the direction of full-scale implementation and commercialization of CCUS technologies. While the Houston workshop focused on early stage research in CO_2 capture, utilization and storage, this workshop focused on strengthening collaboration between industry sectors and research institutions, and public and private sector, by identifying RD&I gaps of common interest in technologies at higher TRL. The intention was to focus on potentials and possibilities, that could yield results and full-scale implementation in the short to medium-term perspective. The objective of the workshop was to contribute in transferring early (low TRL) research activities to development and innovation activities (higher TRL) by developing guidance and development paths for emerging CCUS technologies, and suggestions for new and joint development activities, with the aim of accelerating the commercialization and implementation process.

This report is more compact than the Houston report, as the intention from the outset was to produce a report focused only on recommendations and actions.

About this report

This report presents the results from the Trondheim workshop. The Executive Summary and Recommendations chapter (Chapter 5) presents the recommended actions in short-, medium-, and long-term from the six topics addressed at the workshop: 1) Decarbonizing industry sectors, 2) The role of CCS in enabling clean hydrogen, 3) Storage and CO_2 networks, 4) Storage monitoring, 5) Going climate positive, and 6) CO_2 utilization. Chapter 6 give the topical summaries that were developed by Session Chairs and Secretaries after the workshop. Introductory presentations are found in Appendix 3, and group work session reports, developed and presented at the workshop, are found in Attachment 4.

5. Executive Summary and Recommendations

The purpose of the workshop was to build on and continue the work from the Houston workshop towards implementation and commercialization of CCUS technologies. The specific workshop objective was to contribute in transferring early (low TRL) research activities to development and innovation activities (higher TRL) by developing guidance and development paths for emerging CCUS technologies and suggestions for new and joint development activities. While the Houston workshop focused on early stage research in CO_2 capture, utilization and storage, this workshop focused on strengthening collaboration between industry sectors and research institutions, and public and private sector, by identifying RD&I gaps of common interest in technologies at higher TRL. The intended outcome was a brief report consisting of the guidance and development path documents produced during the workshop, proposals for new and joint development and innovation activities, and a summary of the workshop discussions.

The workshop addressed six different topics; 1) Decarbonizing industry sectors, 2) The role of CCS in enabling clean hydrogen, 3) Storage and CO_2 networks, 4) Storage monitoring, 5) Going climate positive, and 6) CO_2 utilization. The program started with an outline of the expectations for the workshop and status report on the MI Challenge CCUS. After that, introductory overview presentations were given by international experts as motivation talks before the group work sessions. Key messages in the introductory presentations were: 1) status, progress, potential and role, 2) key research and innovation challenges, and 3) steps towards closing gaps for deployment and industrial opportunities.

During the group work sessions, the following questions were addressed: 1) Which opportunities are identified from an industrial point of view?, 2) How do we most effectively get from research to commercial product?, and 3) What joint activities could be established to accelerate technology development and implementation?

Recommendations for actions for the different topics in short-, medium-, and long-term are:

Decarbonizing industry sectors (topic 1)

Recommended short-term actions (within 1 year)

1. To establish joint initiatives, bringing multiple stakeholders from different sectors to increase the probability of project success, share learnings, and catalyse the public acceptance.
2. To implement guidelines, standards, and financial structures to accelerate deployment, e.g. standardized processes to obtain permits, de-risking investments for the "first movers" and ensure reliability over the long term, or funding instruments to support technologies at higher TRL.

Recommended medium-term actions (1 – 3 years)

1. To transfer learnings between countries/regions.

Recommended long-term actions (> 3 years)

1. To implement incentives for low CO_2 value products that encourage consumers to buy low CO_2 footprint products could enhance the business models.

The role of CCS in enabling clean hydrogen (topic 2)

Recommended short-term actions (within 1 year)

1. Existing ideas and plans for industry clusters and infrastructure for transport of H_2 and transport and storage of CO_2 should be funded through public-private partnerships to further develop plans to a final investment decision.
2. Careful safety and impact analysis for design and operational phases should be initiated as part of gaining public acceptance.

Recommended medium-term actions (1 – 3 years)

1. RD&D activities should be accelerated to reduce the cost and carbon footprint of H_2 production with CCS. This can be done through, for example, further developing CO_2 capture technologies, process intensification and increased capture rates, as well as improving understanding of energy and purity requirements.
2. Front-end engineering and design (FEED) should be carried out for industrial clusters with H_2 production and CCS.
3. Policies and regulations that encourage hydrogen as a substitute for fossil fuels and at the same time spur the use of CO_2 should be implemented. This will expand the hydrogen market beyond the present one.

Recommended long-term actions (> 3 years)

1. Detailed design for large-scale industrial clusters and infrastructure should be performed.
2. Construction, commissioning and operation of large-scale clusters and infrastructure must start.

Storage and CO_2 networks (topic 3)

Recommended short-term actions (within 1 year)

1. Engage strongly with the public authorities of each Mission Innovation country so that they are aware of this underground carbon sink technology and can decide to include it in their revised Nationally Determined Contributions (NDCs) and strategies to mitigate climate change.
2. Urge them to initiate pilots, demos and real projects (beyond lab-scale) for field-testing and technology development in real conditions. Such projects will have a key public perception role, enabling local consultation and local technology demonstration.

Recommended medium-term actions (1 – 3 years)

1. Launch an international cooperative project that could be named “Earth Geonome Project” or “Underground Carbon Sink Project”, following a similar model to other famous scientific initiatives, such as Earth Biogenome Project, Integrated Ocean Drilling Program and the International Space Station. This cooperative project with many participating countries and companies could boost national mapping of CO_2 storage resources and address topics too expensive to be addressed by each participant alone, such as providing a big international test site.
2. Address the perception issue of CO_2 storage, which still exists among public authorities and the general public. This includes a proactive communication on risks and mitigation actions balanced with information on benefits, following the example of NASA’s approach. Besides site performance risks, economic, market failure and public perception risks have to be addressed.
3. Launch a Mission Innovation Platform for sharing stories, knowledge, data and case studies, and demonstrate transparency and openness. This would enable a better, wider use of existing technical knowledge. This would also facilitate public communication and risk quantification.

Recommended long-term actions (> 3 years)

1. Establish one or more internationally recognized CO_2 storage open-source software, as done with climate models. Such open-source software would enable transparency, openness and wider collaboration.
2. Mature an international certification process for bankable CO_2 storage resource. This would give more certainty on expected injectivity and storage capacity, while ensuring storage integrity. An independent body could deliver certificates of storage capacity, which would facilitate the efficient planning of CO_2 storage and transport networks.
3. Engage with the insurance and financial communities to build confidence in CO_2 storage, manage the risks, incentivize implementation of CO_2 storage and transport networks, and to manage penalties if promises are not achieved.

Storage monitoring (topic 4)

Recommended short-term actions (within 1 year)

1. Develop innovative ways to show plume stabilization that avoid limitations of "tracking plume boundaries" through international collaboration on pilot closure projects, such as sharing information on large and/or existing projects such as Ketzin, Tomokomai, Otway or Aquistore projects. Working collaboratively on the same problems would facilitate technology development and common understanding.
2. Develop terrestrial sensors for deployment at shallow depths that can measure several parameters of interest at once for process-based approaches to identifying and attributing near surface anomalies.
3. Develop methods to combine tools that take physical measurements for locating offshore features (e.g. chimney-form leakage plumes) concurrently with geochemical measurements for attribution and quantification of associated signals.

Recommended medium-term actions (1 – 3 years)

1. Produce useable outcomes from large data sets to look at artificial intelligence and how other industries (e.g. medical) manage large data sets.
2. Develop smart-monitoring solutions for locating legacy wells (onshore and offshore) that have been plugged and cut off below surface and for assessing their integrity during and after storage operations. This activity will require co-operative field testing under controlled failure scenarios.

Recommended long-term actions (> 3 years)

1. International collaboration to reduce risk and cost on offshore CO_2 demonstration injection project(s) in diverse settings.
2. Decide how much and what types of data to collect to reduce costs and provide assurance using environmental monitoring. For example, developing monitoring workflows that target shallow monitoring to areas of higher risk (e.g. faults and wells) or implementing shallow monitoring only when triggered by anomalous plume behavior in the reservoir were deemed desirable. In this case, better characterization of the overburden is needed to link these zones.

Going climate positive (topic 5)

Recommended short-term actions (within 1 year)

1. Establish R&I activities at scale for climate positive solutions at national and global level.
2. Quantify bio-char possibilities and the global implications. What is the actual potential of BECCS in a complete sustainability context?

3. Support the deployment of climate positive solutions for waste-to-energy plants, the modularity of these and how long-term storage can be secured for the captured CO_2.

Recommended medium-term actions (1 – 3 years)

1. MI should establish a separate climate positive innovation challenge, MI Challenge #9 - climate positive solutions (CPS). As an immature topic it could be very well suited for concerted global action building on knowledge sharing and joint development.
2. Underpin activities to establish a global stocktake (terrestrial and marine-unconventional biomass) of photosynthesis-based materials. Algae—including macro algae—can play a role here but also new ideas like capturing CO_2 from water. We simply do not know which opportunities the ocean space can offer to remove carbon in a sustainable way.
3. Design a quota and certificate system for net removal of carbon dioxide, paving the way for a business model for pure removal technologies offering no other services than removing carbon from the cycle.
4. Establish acknowledged LCA analyses for the various pathways and solutions proposed. This will make it possible to sort out processes and pathways that are not climate positive or not even climate neutral. There is no time to waste on pursuing solutions that do not offer real climate benefits.

Recommended long-term actions (> 3 years)

1. Based upon research and innovation actions start operating pilot plants and demonstration plants for the less mature/high potential technologies.
2. Build systems that allow for investment into CPS based upon business models that pay for carbon stored and isolated from escaping into the atmosphere.
3. Raise the awareness of the need of these kinds of solutions as complementary to the primary measures like efficiency, solar, wind, etc. They must never be used as a substitute for direct measures.

CO_2 utilization (topic 6)

Recommended short-term actions (within 1 year)

1. Review mid-term and long-term selection of CCU technologies: CO_2-based fuels could be the best case and achievable scenario for specific sectors (aviation, marine).

Recommended medium-term actions (1 – 3 years)

1. Re-deploy public research funding to low TRL CCU projects to address 2050 carbon neutrality targets and place CCU in the technology portfolio.
2. Collect and finalize LCA and TEA best practices to evaluate the most promising CCU routes, disseminate and convey a better understanding of these tools to policy makers.

Recommended long-term actions (> 3 years)

1. Once most promising routes have been selected and proven, build up on international cooperation to spur investment on R&I and seek to reduce regulatory barriers on selected and most promising CCU routes.

6. Topical Summaries

Decarbonizing industry sectors (topic 1)

The power sector represents approximately 35% of the CO_2 emissions from fossil fuel combustion. These must be reduced by 40% by 2050 according to the IEA ETP B2DS scenario[1]. The main Energy Intensive Industries (EIIs) are steel, cement, chemicals, refining, hydrogen, natural gas, heavy oil, fertilizers, and waste to energy industries. They are key in the global economy and represent approximately the 25% of global CO_2 emissions. Under the IEA ETP B2DS, the CO_2 emissions from the EIIs must be reduced more than 70% by 2050[1]. The main decarbonisation measures for power and EIIs are renewables, nuclear, fuel switching, increasing energy efficiency, advanced production technologies, and CCUS[1].

Which opportunities are identified from an industrial point of view?

CCUS is essential to provide flexibility and resilience to a low carbon electricity grid [1, 2], covering the intermittency of renewables and offering a cheaper decarbonising solution[2]. Specific arrangements of CCUS units will not impact the existing facility as they will be installed downstream, resulting in a relatively easy integration of the full capture system without deep modification of the existing facility or the electricity grid.

The CO_2 concentration in power plant gas streams can be advantageous for CO_2 capture. Specific EIIs emit gas streams with higher CO_2 concentration than those in power plants, which could offer a further reduction of the CO_2 capture cost. EIIs emit CO_2 directly or indirectly through burning fossil fuels for energy supply, but some EIIs also emit CO_2 as an integral part of their process chemistry. Those process emissions can represent up to 70% of the total CO_2 emissions in specific EEIs [3], and so those EIIS cannot be decarbonised at high rate without CCUS.

The implementation of BECCS (Bio-Energy with CCS) [20, 21] offers deeper CO_2 emissions reduction in power plants and EIIs, with the opportunity to reach negative or net-zero emissions scenarios at reasonable cost [4, 5].

EIIs offer the opportunity of partial CO_2 capture arrangements, which can reduce the CO_2 capture cost, decrease the impact of the integration of CCUS units, and offer intermediate steps along the scale up to full capture configurations [6, 7].

The energy/heat/steam integration with the CCUS unit can be optimized, based on regional, local, and site-specific conditions (e.g. waste heat from the process available to invest on the CCUS unit, or a low carbon intensity of the electricity grid), which can reduce CO_2 capture costs and/or help to achieve specific emissions goals [3, 6, 8, 9].

A number of CO_2 capture systems, such as calcium looping for cement production, can offer a convenient material integration between the CO_2 capture unit and the production process [9-11, 22].

CO_2 utilization (within a CCU or CCUS structure) can offer an additional source of revenue [12]. EIIs might be located in clusters, which offers potential opportunities for implementing common infrastructure and integration, sharing risks and reducing costs [13, 14, 19].

[1] Compared to the Reference Technology Scenario (RTS). Source: https://www.iea.org/etp/explore/

[2] Compared to the scenario without CCUS

How do we most effectively get from research to commercial product?

The power sector has gained significantly more experience on CCUS through years of research and demonstrations compared to most of the EIIs. Knowledge transfer between the power and EIIs, and between different EIIs will speed-up the development of CCUS.

Building pilots, demos and test centres is essential to increase maturity and gain operational experience. Joint initiatives bringing multiple stakeholders from different sectors will increase the probability of success, as will understanding start-up/shut-down performance of CCS in the context of a net zero energy system.

Knowledge sharing, and openness is key, from academia to private partners. Examples include:

- Data sharing: international test centre network(s) are a good platform for harmonizing data, bringing information from learnings, promoting repetition of successful cases, and catalysing the processes standardization
- IP-sharing: it is essential to find a balance between protecting IP and sharing knowledge
- Building a projects database based on experience: it will allow the identification of risks and key metrics to tailor systems and evaluate the potential success of new projects

Incremental scale-up (linear and iterative) by CO_2 emissions sources or size would reduce the project/process risks and effectively ensure optimum integration. This will speed-up the pathway to reach commercial scale at reduced cost.

What joint activities could be established to accelerate deployment?

Common test centres, non-profit organisations, or sectorial research associations can accelerate the CCUS deployment by building up a common ground. Public engagement and social engineering (including non-conventional stakeholders) in parallel with technology development is vital for catalysing the public acceptance.

In the long term, the implementation of guidelines and standards will be key to accelerating deployment. For example, standardizing processes to obtain permits, follow steps within a constructability plan, or to evaluate the project success. The transfer of knowledge and business models between different sectors, and from one plant to another, would too accelerate deployment.

Existing financial structures (revenue models, risk management, funding, capital & ownership [15]) could be effective, along with the following:

- Incentives for low-CO_2 value products and encouraging consumers to buy low CO_2 footprint products will potentially drive down the market price
- Funding instruments to support technologies at higher TRL (between 4 and 8) will help to overcome the “Valley of Death”
- Transfer of learnings, business models and financial aspects from other sectors (such as deSO_x and deNO_x processes)

EIIs can be located in clusters [19]. Joint activities incorporating the interaction between industries, such as products, steam, or energy, can enhance the business model and accelerate deployment. Also, although the cost of CCUS has a substantial impact on the initial product price (for example, cement), that is not a major part of the final product cost (for example, a house). The business model should assume the CCUS cost along the entire product chain to mitigate the impact on the plant owner [16, 17].

Methods to mobilize national efforts towards international efforts include the implementation of a joint procurement commitment [18]. A balance of effort is needed between:

- Private: e.g. to enhance the company image
- Local: e.g. competition for the title of "green city"
- National: e.g. national decarbonisation commitments
- Regional: e.g. European projects
- Global: e.g. international agreements

Local and national support to build common and flexible infrastructures will accelerate deployment. The manufacturer or power producer can focus on the capture process while transport and storage/utilization are managed externally and separated from their business.

In addition, the transfer of learning between countries/regions, for example the experience on the 45Q, will be an important factor. Public support could help to de-risk the investments made by the "first movers" and ensure reliability at long term. Over the time, the public partnership might have a smaller role because the market will take over.

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The Role of CCS in enabling clean hydrogen (topic 2)

Which opportunities are identified from an industrial point of view?

The overarching driver is the quest for a low-carbon society. Although the current regulatory framework is not sufficient to make sure that CO_2 emissions will decrease to net-zero, an increasing number of governments are announcing ambitions for significant reductions over the next few decades. Electrification and hydrogen produced by electrolysis with renewable electricity are presented as solutions.

However, there are areas where electrification is unlikely to be used and for which hydrogen is an alternative, such as:

- Heavy duty transportation (large trucks, ships, trains, aircraft)
- High temperature heat
- Industry (reducing agent in steel, feedstock in refineries and other chemical industry)
- Energy storage

Presently, and most likely for the coming decades, hydrogen produced from hydrocarbon fuels (in particular, natural gas) with CCS has a lower cost and carbon footprint than hydrogen produced by electrolysis. This creates more opportunities:

- Production of hydrogen and carbon black and store the solid carbon
- Finding applications also for the CO_2 such as EOR and combination of H_2 and CO_2 in CCU
- Spiking natural gas with hydrogen for transport through existing pipelines
- Achieving negative emissions by gasification of biomass and subsequent hydrogen production with CCS, assuming the biomass meets sustainability criteria

Avoiding transportation of CO_2 across borders (i.e. avoiding restrictions imposed by the London Protocol), by either reforming where the gas is produced, storing the CO_2 there and transporting hydrogen, transporting the natural gas and reforming and storing CO_2 in the receiving country.

Finally, hydrogen produced with hydrocarbons and CCS offers additional opportunities that reuse the extensive infrastructure developed for natural gas distribution and draw on extensive competence in industry, research organisations and academia. Examples of projects mentioned by the participants are H21 [1] and Hynet [2] in UK and H-Vision (Rotterdam) [3] and Magnum [4] in the Netherlands.

The participants also agreed that there is no "one size fits all" approach nor any "silver bullet". It may be envisioned that hydrogen could become the main export from natural gas producing companies by 2050.

How do we most effectively get from research to commercial product?

The team drew on a graph by M. Hekkert, Netherlands, on how several factors need to be fulfilled to have successful innovation. This underlines that market acceptance of new technologies is much more complex than technology development alone.

Activities required to get from research to commercial product were identified. In no particular order:

- Consider the whole value chain and perform value chain demonstrations to build confidence, master complexities, inform choices, and contribute to increased market confidence. This could change market pull to market push and increase public acceptance. Commonalities for hydrogen (compression, storage, transport and infrastructure) can be included regardless of production methods

- Go for large-scale: allows for impact and well-informed decisions, reducing technology risk
- Demonstration project TRL 7-9. These must have a viable business case after project ends
- Go for small scale: room for experiments, allows quick decisions and niches, for example connected to biogas production.
- Start with the "low-hanging fruits", e.g. the H_2/CO_2 from the reforming process
- Academia should inform discussions
- 'Middlemen' are needed to link different stakeholders, suggest opportunities and create industrial symbiosis
- Share knowledge, data and other relevant information (policies, permitting etc)
- In the absence of effective CO_2 regulation or an effective price for CO_2 emission - Government funding – consistent in time – and international level playing field
- International cooperation on test centres to avoid duplications, 'TCM for hydrogen', joint funding and use
- Regulation to mandate low carbon content

Specific R&D activities were identified:

- Increase capture rate without increasing cost
- Understand the energy requirement, purity of CO_2, liquefaction CO_2, etc.
- Reduce the cost of low carbon H_2 production, e.g. further developing sorbent enhanced reforming
- Process intensification (e.g. vacuum pressure swing absorption, ELEGANCY project)
    - Opportunity for energy storage: H_2 or NH_3
    - Public acceptance

What joint activities could be established to accelerate technology development and implementation?

- Encourage international collaboration and joint industry projects where several industrial players can share costs, e.g. demonstration size projects
- Creating a vibrant market for technology vendors
- Encourage industry clusters, where different industrial sectors join around hubs with large-scale hydrogen production with CCS and a common infrastructure. For examples, see [1-4]
- Encourage public-private partnerships
- Support policies and regulations for use of H_2 produced with CO_2 capture
- Honesty about the safety aspects of H_2. Carry out consequence and safety risk analyses in design and operation phases, paying due attention to the properties of hydrogen.

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3. https://www.deltalings.nl/h-vision-en
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Storage and CO_2 networks (topic 3)

Which opportunities are identified from an industrial point of view?

CO_2 geological storage is a key carbon sink, which consists of returning the carbon back to the underground - a virtuous loop for the climate. This carbon sink is needed to achieve the Paris agreement targets and the recent ambitions of carbon neutrality. It does not depend on the climate and weather conditions, compared to the forests & soils carbon sink.

The rising awareness of the climate crisis and the ongoing green and digital revolutions are bringing big opportunities for the full-scale implementation and commercialization of CO_2 transport and storage technologies.

Large-scale CO_2 storage will create an enormous business potential: the technical know-how is there to get started and young people are motivated to work on green topics. There are opportunities for new business including independent assessment bodies and for added-value complementary activities, such as water production, EOR, energy production and storage, and more.

Cost-effective CO_2 storage and transport hub systems can be developed. A cluster approach by geographic area, with a portfolio of storage sites connected to CO_2-emitting plants, reduces the risks and costs while allowing tailored solutions to local contexts.

The revolution in digital technologies (big data, machine learning, artificial intelligence) applied to CO_2 storage & transport networks is a big opportunity to deepen the knowledge on the multi-scale and multi-physics processes underground, improve the modelling and monitoring tools and strategies, plan and manage the transport and storage operations, visualize them, share data and knowledge, and facilitate the interaction with all stakeholders.

These points should help to better address the perception issue of CO_2 storage, which still exists among both public authorities and the general public. It is important to further develop methods to quantify project risks and benefits, and to mitigate unexpected events. Besides site performance risks, economic, market failure, and public perception, risks must be addressed.

How do we get most effectively from research to commercial product?

Pilots, demos and real projects (at scale beyond lab) are needed to field-test and develop technology in real conditions. They will also have a key role in public perception by enabling local consultation and technology demonstration.

There is a need to mature R&D technologies in specific fields such as pressure management, fault & fracture risk, well integrity, resource optimization/mobility control, pipeline fracture propagation, and network & hubs planning tools. This most often requires pilots, demos, and applications in full-scale projects.

An international cooperative “Earth Genome project” could be created following a similar model to other famous scientific initiatives such as the Earth Biogenome Project, Integrated Ocean Drilling Program, or International Space Station. Such a project with multiple participating countries and companies could boost the national mapping of CO_2 storage resources and address topics too expensive to be addressed by each individual participant, such as providing a large international test site. Also, Mission Innovation twinning projects could partner two or more countries on specific projects such as technology development, pilot & demonstration. Twinning of countries with CCS experience with developing countries would facilitate the global dissemination of CCS.

Transparency and openness is key. This includes the sharing of data and results from all the technology development steps. This also includes proactive communication on risks and mitigation actions, balanced with information on benefits. The approach of NASA is a good example.

Finally, regulatory rules have to be set up to facilitate the path to commercialization of CO_2 transport and storage technologies.

What joint activities could be established to accelerate technology development and implementation?

Joint international efforts are important to accelerate technology development and implementation of CO_2 storage and transport networks at national level. There are several potential joint activities.

Firstly, data sharing and the use of international digital platforms. Subsurface data collection could be mandated by the public authorities and data sharing could be mandated by law or stimulated by public incentives such as tax. Furthermore, a Mission Innovation Platform for sharing stories, knowledge and case studies could be established to enable a better, wider use of existing technical knowledge. This would also facilitate public communication and risk quantification.

Maturation of an international certification process for bankable CO_2 storage resource would be advantageous. This would give more certainty on expected injectivity and storage capacity and ensure storage integrity. An independent body could deliver certificates of storage capacity, which would facilitate the efficient planning of CO_2 storage and transport networks. Future work can build on the practical approach currently being developed to maturing CO_2 Storage Readiness Levels (SRLs) and on the CO_2 Storage Resource Management System framework (SRMS) for resource reporting, similar to the classification systems for petroleum resources.

One or more international open-source CO_2 storage software could be established, as with climate models. Such software would enable transparency, openness and wide collaboration. Standardization of terminology and processes should be pursued to guarantee common understanding and approaches, and to enable quicker development and implementation.

Engagement with the insurance and financial communities is needed to build confidence in CO_2 storage, manage the risks, incentivize implementation of CO_2 storage and transport networks, and manage penalties if promises are not reached.

Stronger engagement with the public authorities of each Mission Innovation country is needed so that all are aware of the carbon sink technology, with a view to including it in their revised Nationally Determined Contributions (NDCs) and strategies to mitigate climate change.

Storage monitoring (topic 4)

The following five challenges were viewed within the context of upscaling CCUS, which may require projects to operate in close proximity:

- Monitoring to demonstrate containment and enable site closure: transforming far-field monitoring with new tools to directly measure state variables
- Smart monitoring in the far-field
- Improving methodologies for monitoring plans
- Improving interpretation and use of large, complex data sets
- Assessing anomalies and providing assurance – location, attribution, quantification

The overall goal of the discussion was to define the ways in which approaches and technologies in monitoring, verification, and performance could be accelerated from research to commercial applications through joint international collaborations and to explore the business models and funding instruments that might facilitate this development.

Three of the challenges: smart monitoring, monitoring plan methodologies, and interpretation and use of large, complex data sets were applicable to all areas of monitoring and were therefore incorporated into the broader topics of site closure and anomaly detection. It was further decided that a gap existed in the original report around monitoring the integrity of legacy wells. This is critical to long-term subsurface CO_2 containment, so the topic was added to the discussion.

Recurring themes

Themes common to all topics included reducing cost while increasing accuracy, developing monitoring workflows that are flexible and dynamic, industry and research collaboration on international projects, and data sharing. Producing useable outcomes from large data sets was identified across all groups, with a suggestion to look at artificial intelligence and how other industries such as medical manages large data sets.

Co-operative "learning-by-doing" activities were consistently described as important to drive technologies forward. International R&D funding mechanisms like *Accelerating CCS Technologies (ACT)* (http://www.act-ccs.eu/) are critical as well as public-private partnerships and country co-funding.

An important aspect for transitioning from research to commercial application is to use vendors to eliminate uncertainties thorough testing and trials of tools. Learning through international collaborations on projects that put CO_2 into the ground, especially offshore, is thought to be the most impactful activity.

Closure and far-field monitoring

Stabilization of plume boundaries must be documented for site closure. However, monitoring the plume in the far-field is especially challenging. This is mainly because current monitoring methods are indirect and limited to point source measurements. Such monitoring will become even more challenging during scale-up when multiple projects operate in proximity to one another.

International collaboration on pilot closure projects was identified as important for progressing this challenge. Sharing information on large and/or existing projects such as Ketzin, Tomokomai, or Aquistore projects and working collaboratively on the same problems would facilitate technology development and common understanding. Evaluating and comparing differences in existing models and settings for closure (e.g. Norwegian, Canadian, and Texan models) would aid tool choice and application as well as to develop flexible and staged monitoring workflows. Digital "twins" or replicas of projects could be used to explore unlikely scenarios without causing public confusion over CO_2 containment within the project.

Co-operation among neighboring fields and/or the co-use of existing infrastructure and data sharing was deemed important for this challenge. In the far field, signals from neighboring projects can be detected and used for understanding systems on a regional scale.

Ways in which centralized organizations might facilitate co-operative monitoring activities should be explored to foster harmonious management of adjoining storage projects. For example, assessing pressure interference among wells (both vertical and horizontal) among projects at scale would provide critical information to evaluate the value of monitoring information and testing the impact of reducing information towards achieving closure. Gaining this information would inevitably lead to more fit-for-purpose tool development and smoother large-scale storage operations.

Assessing anomalies and providing assurance

Monitoring to provide assurance depends largely on recognizing and attributing the source of anomalous signals. Cost effective, accurate methods that can show compliance to regulations and foster public acceptance are critical. As upscaling occurs, methods to respond to the concerns of stakeholders living near projects will also be needed.

With the awareness that climate change is creating shifting baselines, moving away from baseline comparisons toward more process-based approaches was deemed important by the working group. Deciding how much and what types of data to collect to reduce costs and provide assurance is important. Data collection for monitoring a CCUS project could benefit from coordinating with other similar ongoing data collection activities such as offshore seawater column monitoring in an offshore setting.

Monitoring workflows that target shallow monitoring to areas of higher risk (e.g. faults and wells) or implement shallow monitoring only when triggered by anomalous plume behavior in the reservoir were deemed desirable. In this case, better characterization of the overburden is needed to link these zones. Combining tools that take physical measurements for locating features concurrently with geochemical measurements for attribution and quantification (if necessary) of associated signals in the offshore environment is an optimized strategy that will contribute to cost effectiveness. Process-based approaches will require sensors that can measure several parameters of interest at once.

Legacy well monitoring

Leakage from legacy wells remains one of the higher risks for loss of containment, yet smart technologies are not available for their overall assessment. Smart monitoring tools for locating legacy wells and interrogating them for leakage potential would be transformational towards lowering risk. Approaches to define and measure thresholds above which intervention is required are needed but do not currently exist. The types of data (active-passive methods) that can be collected to deal with uncertainty, manage cost overhead, deliver project transparency, and illustrate successful remediation have not yet been determined. In the event of well failure, monitoring to indicate remediation efforts are effective and/or to quantify emissions are also of interest. In short, establishing procedures for well integrity testing and implementing a certification framework will aid in fulfilling legal, regulatory, and spatial project planning and aid in communicating and assuring safety to the public. Similarly, developing monitoring methods for finding and characterizing small-mid size faults that could be below the resolution of current imaging technology is a technology improvement opportunity.

The types of data needed for legacy well monitoring must be identified and developed before procedures can be established. Monitoring technology will govern and establish these procedures. These advances will need to be field tested under controlled well failure scenarios. Once these methods are available, they can be implemented by specialized agencies to respond to leak emergencies. The outcome of developing these technologies could be to establish a centralized team to advise/intervene when needed and form an advisory “peer-review” panel to help “certify” CCS projects.

Going climate positive (topic 5)

This session dealt with what is commonly described as carbon negative technologies or CO_2 removal technologies. The need for these solutions has become evident as emissions from agriculture (non-CO_2 gases) and various process emissions are partly or fully unavoidable, thus net GHG removal technologies are needed.

Such GHG removal technologies have been identified in various recent reports (Royal Society, Akatech) and range from mineralization via the weathering of minerals to bioCCS and direct air capture (DAC). These technologies provide nothing else than removal of greenhouse gases and as such have a significant market introduction barrier.

They are also resource intensive, be it the amount of minerals needed for natural weathering at scale, the amount of renewable power needed for DAC to make a difference, water usage or the volume of biomass needed for bioCCS to offset significant "unavoidable" emissions in the future.

These technologies only make sense when the resources that are needed for them to work are sourced sustainably. That should always be assessed by LCA analyses. A fast mover within the area is CCS on waste-to-energy plants, where the feed can have a biogenic content of up to 75%, providing a net removal of CO_2 from the atmosphere.

Which opportunities are identified from an industrial point of view?

DAC can make sense from a commercial point of view when supplying CO_2 from the air at competitive prices to commercial CO_2. Such markets exist today and when cheap electricity and heat can be used at low cost – for instance in islands or in high cost products.

BioCCS is happening in the UK (pilot Drax) and can also be done commercially. In principle the three routes for capturing CO_2 – post-combustion, pre-combustion and oxy-fuel — can all be employed for biomass too.

Other opportunities include:

- Negative emission technologies need policy & incentives
- Fuel production can be a commercial bridge to advance negative emission technologies. The question about time and urgency can make this slowing the rate of change of real emission reductions
- Niche applications first, but still will need public support (e.g. direct air capture start-ups)
- Biomass gasification with CCS: carbon efficiency varies by application. Transport of biomass is costly, and logistics can be a challenge.
- Huge demand on terrestrial biomass sources, land use issues. This needs to be sustainable, otherwise other negative environmental issues are created. There is potential friction with Sustainable Development Goals. The Ocean space could offer new resources and solutions.
- Challenge: full carbon accounting is not fully understood and agreed upon. Solutions may vary locally
- Need to get clear understanding and framework under which conditions which technology might be best solution (lots of information exists, but not in one place).
- Connection with waste-to-energy can create commercially viable plants (municipal waste, pulp & paper)
- Modular capture plants for small-scale application at town level, especially feasible for waste-to-energy plants. Long-term storage for small sources still represents an issue.
- Biomass and secondary biomass will be important feedstocks

How can we most effectively get from research to commercial product?

Even if the technologies are mostly known for bioCCS, there is a lack of a R&I agenda for GHG removal technologies beyond CCS such as biotechnology and biochar applications (can also be combined with CCS). Furthermore, it remains to be seen how much biomass can be harvested sustainably from the ocean.

Therefore, it is both mature and early days for climate positive solutions. What is clear is that the terrestrial sources of biomass for curbing climate change are limited and very soon reach conflict with food production storing CO_2 in trees, water usage and transportation issues. Each value chain has to be investigated to ensure sustainability.

Other notes include:

- Biochar as solution in parallel with CCS? Enhances soil carbon content. But needs public education and acceptance (ref. Acatech position paper on biomass use – March 2019).
- Biochar storage as option (bioenergy-biochar systems – BEBCS).
- What is the "agency" for carbon accounting? Markets? Certification frameworks? Start somewhere, even if certification is imperfect. Expert bodies? Markets? Governments need to set right incentives?
- What is the actual potential of BECCS? Insufficient knowledge – one could argue that the present biomass use is larger than sustainable – need to make use of waste streams from biomass.
- Some plants exist already, e.g. ethanol production, others in waste-to-energy.
- Suitable business models need to be developed: like waste removal, service model of taking CO_2 emissions problem away from people / credits.
- So far, a lot of research has focused on biofuels. Other applications will need large pilots.
- Get commercial biomass conversion applications going (worry about CO_2 capture and sequestration part later)
- Address remaining technology challenges for conversion of trees (e.g. in California) to produce RNG (Renewable Natural Gas)
- Ocean based biomass production should be explored more. Large potential, but not as well understood as terrestrial biomass management. This represent an under-researched area and white spot on the map for curbing emissions.
- Still more large-scale pilot and demonstration is needed, requires large-scale financing ($100 million range). Need connection to product market.
- Challenges in "Bio-CCS" are mainly in the "Bio"-management part, not so much in the "CCS" part (more or less similar to fossil CCS).

There needs to be a global resource stock take of terrestrial and marine unconventional biomass. Algae and marine biomass can become very important as long as sustainability is ensured. We also need to recognize the cost of carbon and account for damages in our economic models.

What joint activities could be established to accelerate technology development and implementation?

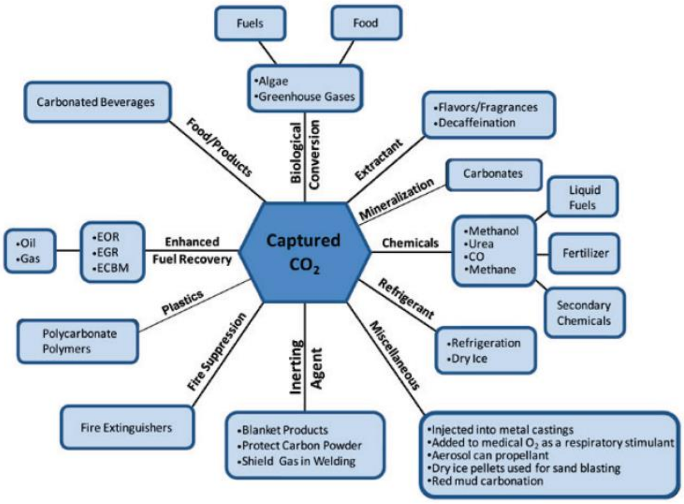
There is a need for more unified, international efforts, and to talk more about "climate positive solutions" rather than carbon negative solutions or reducing CO_2 emissions. A good example is the public acceptance of direct air capture, which apparently has a workable business model.
There is also a need to integrate value chains and consider options such as Aker Solutions' cheap modularized capture plants. CO_2 infrastructure is still required.

Other potential activities include:

- Emphasising the importance of knowledge sharing and standardization of best practices

- Leverage R&I cooperation – global broker for climate positive solutions using accounting principles
- Cost of carbon consumption and scaling up needs to be reflected
- Leverage and manage consumer purchase power
- Certification and standardisation of climate positive effects are important and should be pursued
- MI should establish a separate climate positive solution challenge – MI Challenge #9 – Climate positive solutions (CPS)

CO_2 utilization (topic 6)



Courtesy of NETL (from Mission Innovation Carbon Capture, Utilization, and Storage Workshop, Houston 2017)

The CO_2 utilisation topic was discussed within 4 sub-topical groups: fuels/chemicals/plastics, mineralization/building materials, CO_2-Enhanced oil recovery (EOR) and a transverse sub-topic aiming at investigating market/thermodynamics of CCU routes in general.

Generally speaking, participants felt most CCU routes do not provide massive decarbonisation pathways compared to CCS, as CO_2 will be released into the atmosphere on a short-to-medium term basis.

Opportunities identified from an industrial point of view

Studies showed that there is opportunity in markets of all sizes for all CCU routes, although the competitive advantage varies. Updates of these studies should take into account the market's evolution. CCU has a better public acceptance than CCS, so there is an opportunity to build trust among parties and then transfer it to the CCS by increasing synergy between CCU and CCS.

In some cases, decarbonisation by other means will be difficult to achieve. For example, in air transportation and the marine sector, CO_2-based products might be considered among the best options.

However, as oil and gas production is set to decline, CO_2-EOR offers GHG emission reduction during energy transition as a proven technology at commercial scale, albeit mainly in the US. One of its main advantages is the potential reuse of existing facilities such as wells and other infrastructure to demonstrate CO_2 storage at large scale.

Mineralization is singled out as the main opportunity for utilization as far as market size is concerned. It also provides the market with a CCU substitute which does not disrupt the conventional one. In addition, new CCU mineralization plants could fit within the proximity of industries that would provide CO_2 streams and material for the construction and civil works, such as steel and glass.

Getting more effectively from research to commercial product

A prerequisite to consider a CCU product as a commercial product is to assess its potential in terms of GHG emission reduction. Consistent life cycle assessment (LCA) and techno-economic assessment

(TEA) should identify the most promising CCU routes. Boundaries of these studies are as important as the lifecycle of the technologies. Specific attention to the potential of GHG reduction should be addressed when different H_2 sources or CO_2 feedstock are considered.

There are several lessons learned across the sub-topics. Polymers count a few success stories from research to commercial scale but remain case specific. Research much aim at focusing on CO_2 based chemicals which requires less modifications as a first step. In the mineralization/building materials field, more pilots should be supported to assess and improve mineralization technologies. Research should also focus to improve technologies which are processing directly flue gas instead of purified CO_2. Conversely, as the technology is already proven and deployed at commercial scale, only low TRL should be considered to improve CO_2-EOR process technologies aimed at sustainable economic and environmental benefits. In addition, R&I is required to expand storage capacity.

Overall, capture technologies are crucial for CCS and for CCU. It is one of the main barriers. Over the years to come, CO_2 will be available in large amounts and without higher efficiency in capture, the cost for using or storing CO_2 may be too high. It will remain one of the main priority research areas, especially on high energy efficiency processes, to drive the product to the market: Thermodynamics need to be tackled for most CCU routes.

Joint activities to be established to accelerate technology development and implementation, joint action to accelerate deployment. Business models and funding instruments to be more effective. Mobilizing national efforts towards international efforts Public-private partnership, co-funding

CO_2-based products have higher cost compared to fossil-based products. CCU needs primarily joint action in the field of legislation. Mechanisms should be set up by governments such as CO_2 tax or other regulations. Related to the potential of its GHG emission reduction, incentives for this kind of technologies should be questioned because their mitigation potential still needs to be demonstrated. For some CCU pathways, it is currently limited. Nevertheless, there are ample activities which can be undertaken with joint action.

In particular, to assess the benefits of mineralization for storing CO_2 within building material, a joint activity is required as the construction industry is standardized. Addressing this issue at the national scale only will probably not be efficient. As an outcome of such an initiative, a label endorsing both the duration and the amount of CO_2 stored within a given type material, would help to create a market for this low-carbon product and will circumvent partially the difficulties stemming from their higher price tag.

Legislation issues could also be addressed within international partnerships. In some countries, legislation is a hurdle for the development of carbonization using waste materials: for instance, in France and Germany regulation prevents waste material from being used as base material for CCU mineralized aggregate. There is also a need to work on specifications for these new products. Technical, safety and environmental aspects need to be addressed through international collaboration to extend the full potential of these CCU pathways in terms of quantities and benefits. In the case of CO_2-EOR, additional funding is not a prerequisite as it is already fit for commercialization. However, a clear framework should be set up by public authorities to disseminate and demonstrate its potential for GHG emission reduction during a transitional period. This could be achieved through international collaboration on standards, ensuring anthropogenic CO_2 is used for enhanced oil recovery rather than natural CO_2 extracted from subsurface. In addition, low TRL research requires international collaboration.

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Appendix Section

Appendix 1: About the Workshop

Appendix 2: Workshop program

Appendix 3: Introductory presentations at the workshop (slides)

Appendix 4: Presentations from group work sessions (slides)