

## Mission Innovation Challenge CCUS Workshop Summaries

June 19-20, 2019  
Scandic Nidelven Hotel  
Trondheim, Norway

### Workshop abstract

The two-day workshop gathered 125 participants and had six different topics:

1. Decarbonizing industry sectors
2. The role of CCS in enabling clean hydrogen
3. Storage and CO<sub>2</sub> networks
4. Storage monitoring
5. Going climate positive
6. CO<sub>2</sub> utilization

After a welcome address by Nils A. Røkke (SINTEF) and a Mission Innovation status report by Brian Allison (BEIS), introductory presentations were given to all topics in a plenum session. The first three topics were discussed in parallel sessions in the evening and morning of June 19, while the last three topics were discussed in parallel sessions on June 20. Results from session discussions were presented in a plenum session as a conclusion of the workshop.

The plan is to issue the final results from the workshop by mid-October 2019. The plan includes the following steps:

| Action                                                                                                           | Responsible      | Deadline |
|------------------------------------------------------------------------------------------------------------------|------------------|----------|
| Adjustment of presentations and draft executive summary (maximum two pages) sent to organizers                   | Session Chairs   | July 3   |
| Compilation of presentations and draft exec. summaries sent to all participants included "no-shows"              | Organizers       | July 5   |
| Comments to presentations/draft exec. summaries sent to Session Chairs                                           | All participants | Sept. 6  |
| Final versions of presentations/exec. summaries sent to organizers                                               | Session Chairs   | Sept. 17 |
| Add overall summary from the workshop                                                                            | Organizers       | Sept. 17 |
| Send out complete report (overall summary, exec summaries, and presentations) to all for final round of comments | Organizers       | Sept. 24 |
| Send final comments to organizers                                                                                | All participants | Oct. 4   |
| Final report completed and disseminated                                                                          | Organizers       | Oct. 11  |

In refining the preliminary results from the workshop, both attendees and no-shows are invited to provide input.

**Executive summaries** from the sessions are found below.

## Workshop program

JUNE 19

**17:00 Welcome and introduction** (program, expectations for the workshop)

[Nils A. Røkke, SINTEF](#) and [Brian Allison, BEIS UK](#)

**17:10 Status of Challenge #3** (recap of Houston workshop, Houston report, etc.)

[Brian Allison, BEIS UK](#)

**17:30 Introduction to topics (12 minutes each)**

[Session Chair: Brian Allison, BEIS; UK](#)

1. Topic 1: Decarbonizing industry sectors (power, cement, refineries, steel, fertilizers...)
  - Introductory speaker: [Monica Garcia, IEAGHG](#)
2. Topic 2: The role of CCS in enabling clean hydrogen
  - Introductory speaker: [Sigmund Størset, SINTEF](#)
3. Topic 3: Storage and CO<sub>2</sub>-networks
  - Introductory speaker: [Phillip Ringrose, Equinor](#)
4. Topic 4: Storage monitoring
  - Introductory speaker: [Tip Meckel, Gulf Coast Carbon Center](#)
5. Topic 5: Going climate positive (biomass, waste to-energy, resources and technology)
  - Introductory speaker: [Niall MacDowell, Imperial College London](#)
6. Topic 6: CO<sub>2</sub> Utilization
  - Introductory speaker: [Jaap Vente, TNO](#)
  - "Success story" speaker: [Mark Summers, Emissions Reduction Alberta \(ERA\)](#)

**19:00 Dinner (buffet-style)**

[Briefing session for Session Chairs and Secretaries \(separate room\)](#)

**20:00-22:00 Group work over topics 1-3**

Session/Topic 1: Decarbonizing industry sectors (power, cement, refineries, steel, fertilizers...)

Chair: [Mike Monea, CCS Knowledge Centre](#)

Secretary: [Stefania Osk Gardarsdottir, SINTEF](#)

Room: [TBA](#)

Session/Topic 2: The role of CCS in enabling clean hydrogen

Chair: [Lars Ingolf Eide, Research Council of Norway](#)

Secretary: [Gerdi Breembroek, Netherlands Enterprise Agency](#)

Room: [TBA](#)

Session/Topic 3: Storage and CO<sub>2</sub>-networks

Chair: [Isabelle Czernichowski-Lauriol, BRGM](#)

Secretary: [Peter Zweigel, Equinor](#)

Room: [TBA](#)

**JUNE 20**

**08:30-10:00    Group work over topics 1-3 (cont'd)**

*(Same Chairs, Secretaries and rooms)*

**10:00-12:00    Group work over topics 4-6**

Session/Topic 4: Storage monitoring

Chair: [Katherine Romanak, University of Texas](#)

Secretary: [Tim Dixon, IEAGHG](#)

Room: [TBA](#)

Session/Topic 5: Going climate positive

Chair: [Niall MacDowell, Imperial College London](#)

Secretary: [Nils A. Røkke, SINTEF](#)

Room: [TBA](#)

Session/Topic 6: Utilization

Chair: [Paul Bonnetblanc, Ministry of Ecological Solidarity Transition](#)

Secretary: [Aicha El Khamlichi, ADEME](#)

Room: [TBA](#)

**12:00-12:45    Lunch**

**12:45-14:15    Group work over topics 4-6 (cont'd)**

*(Same Chairs, Secretaries and rooms)*

**14:15-15:25    Reporting (10 minutes each)**

*(To be conducted by the Session Chair, Session Secretary and Introductory Speaker)*

- Topic 1: Monica [Garcia](#), Mike [Monea](#), Stefania Osk [Gardarsdottir](#)
- Topic 2: Lars Ingolf [Eide](#), Gerdi [Breembroek](#)
- Topic 3: Phillip [Ringrose](#), Isabelle [Czernichowski-Lauriol](#), Peter [Zweigle](#)
- Topic 4: Tip [Meckel](#), Katherine [Romanak](#), Tim [Dixon](#)
- Topic 5: Niall [Mac Dowell](#), Nils A. [Røkke](#)
- Topic 6: Jaap [Vente](#), Paul [Bonnetblanc](#), Aicha [El Khamlichi](#)

**15:25    Summary and conclusion**

[Nils A. Røkke and Brian Allison](#)

## Session Topics, Chairs, Secretaries, and Introductory Speakers

### Topic 1: Decarbonizing industry sectors

- Chair: [Mike Monea](#), CCS Knowledge Centre
- Secretary: [Stefania Osk Gardarsdottir](#), SINTEF
- Intro speaker: [Monica Garcia](#), IEAGHG

### Topic 2: The role of CCS in enabling clean hydrogen

- Chair: [Lars Ingolf Eide](#), Research Council of Norway
- Secretary: [Gerdi Breembroek](#), Netherlands Enterprise Agency
- Intro speaker: [Sigmund Størset](#), SINTEF

### Topic 3: Storage and CO<sub>2</sub> networks

- Chair: [Isabelle Czernichowski-Lauriol](#), BRGM
- Secretary: [Peter Zweigel](#), Equinor
- Intro speaker: [Phillip Ringrose](#), Equinor

### Topic 4: Storage monitoring

- Chair: [Katherine Romanak](#), University of Texas
- Secretary: [Tim Dixon](#), IEAGHG
- Intro speaker: [Tip Meckel](#), Gulf Coast Carbon Center

### Topic 5: Going climate positive

- Chair: [Niall MacDowell](#), Imperial College London
- Secretary: [Nils A. Røkke](#), SINTEF
- Intro speaker: [Niall MacDowell](#), Imperial College London

### Topic 6: CO<sub>2</sub> utilization

- Chair: [Paul Bonnetblanc](#), Ministry of Ecological Solidarity Transition
- Secretary: [Aicha El Khamlichj](#), ADEME
- Intro speaker: [Jaap Vente](#), TNO  
[Mark Summers](#), Emissions Reduction

# Executive Summaries

## TOPIC 1: Decarbonizing Industry Sectors

The power sector represents approximately a 35% of the CO<sub>2</sub> emissions from fossil fuel combustion and, under the IEA ETP B2DS, those must be reduced by 40% in 2050<sup>1</sup>. The main Energy Intensive Industries (EIs) 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 the total global CO<sub>2</sub> emissions. Under the IEA ETP B2DS, the CO<sub>2</sub> emissions from the EIs must be reduced more than 70% by 2050<sup>1</sup>. The main decarbonisation measures for power and EIs sectors are renewables, nuclear, fuel switching, increasing energy efficiency, advanced production technologies, and CCUS<sup>1</sup>.

### 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], covering the intermittency of renewables and offering a cheaper decarbonising solution<sup>2</sup>
- Specific arrangements of CCUS units offer the advantage of not impacting the existing facility as those 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<sub>2</sub> concentration in the gas streams in power plants can be beneficial to capture of the CO<sub>2</sub>. Specific EIs emit gas streams with higher CO<sub>2</sub> concentration than those in power plants, which could further reduce the CO<sub>2</sub> capture cost. EIs emit CO<sub>2</sub> directly or indirectly through burning fossil fuels for energy supply, but some EIs inherently emit CO<sub>2</sub> as an integral part of their process chemistry. Those process emissions can represent up to 70% of the total CO<sub>2</sub> emissions in specific EIs [2], and thus those EIs cannot be decarbonised without CCUS.
- The implementation of BECCS (Bio-Energy with CCS) offers a deeper CO<sub>2</sub> emissions reduction in power plants and EIs, with the opportunity to reach negative or net-zero emissions scenarios at reasonable cost [3].
- EIs offer the opportunity of partial CO<sub>2</sub> capture arrangements, which can reduce the CO<sub>2</sub> capture cost, decrease the impact of the integration of CCUS units, and offer intermediate steps along the scale up to full capture configurations[4].
- 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<sub>2</sub> capture costs and/or help on achieving specific emissions goals [4]
- A number of CO<sub>2</sub> capture systems, such as calcium looping for cement production, can offer a convenient material integration between the CO<sub>2</sub> capture unit and the production process[5]
- CO<sub>2</sub> utilization (within a CCU or CCUS structure) can offer an additional source of revenue
- EIs might be located in clusters, what offers potential opportunities for implementing common infrastructure and integration, share risks and reduce costs

### 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 EIs. Knowledge transfer between the power and EIs, and between different EIs will speed-up the development of CCUS
- Building pilots, demos and test centres is essential to increase maturity and gain operational experience.

---

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

<sup>2</sup> Compared to the scenario without CCUS

- Joint initiatives bringing multiple stakeholders from different sectors will increase the probability of success.
- Understand 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 are:
  - 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<sub>2</sub> emissions sources or size would reduce the project/process risks, and effectively ensure the optimum integration. Consequently, it will speed-up the pathway to reach commercial scale at reduced cost.

### **What joint activities could be established to accelerate deployment?**

#### **a) How can joint action 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 accelerate deployment (e.g. standardized processes to obtain permits, to follow steps within a constructability plan, or to evaluate the project success)
- Transfer knowledge and business models between different sectors, and from one plant to another

#### **b) Business models: What funding instruments are/could/would be effective?**

- Existing financial structures: Revenue models, risk management, funding, capital & ownership[6]
- Incentives for low-CO<sub>2</sub> value products and encouraging the consumers to buy low CO<sub>2</sub> footprint products will potentially drive 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 (e.g. the deSO<sub>x</sub> and deNO<sub>x</sub> processes)
- EIs can be located in clusters. Joint activities incorporating the interaction between industries, such as products, steam, or energy, can enhance the business model and accelerate deployment
- For EIs, although the cost of CCUS has a substantial impact on the product price (for example, cement), that is not significant in 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.

#### **c) Mobilizing national efforts towards international efforts**

- Implementation of a joint procurement commitment

- A proper balance is needed between private (e.g. to enhance the company image), local (e.g. competition to get the title of “green city”), national (e.g. national decarbonisation commitments), regional (e.g., European), and global efforts (e.g. international agreements).
  - Local and national support to build common and flexible infrastructures will accelerate deployment. The manufacturer/ power producer can focus on the capture process while transport and storage/utilization are managed externally and separated from his business
  - Transfer of learning between countries/regions. For example, experience on the 45Q
- d) Public-private partnership, co-funding**
- 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

## References

- [1] IEAGHG, “Valuing Flexibility in CCS Power Plants, 2017/09, December, 2017,” no. December, 2017.
- [2] M. Garcia, N. Berghout, and L. Herraiz, “Cost of CO<sub>2</sub> Capture in the Industrial Sector: Cement and Iron and Steel Industries (IEAGHG/2018-TR03),” 2018.
- [3] IEAGHG, “Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass (2019/02),” no. March, 2019.
- [4] R. Skagestad *et al.*, “CO<sub>2</sub>stCAP - Cutting Cost of CO<sub>2</sub> Capture in Process Industry,” *Energy Procedia*, vol. 114, no. 1876, pp. 6303–6315, 2017.
- [5] N. Rodríguez, R. Murillo, and J. C. Abanades, “CO<sub>2</sub>capture from cement plants using oxyfired precalcination and/ or calcium looping,” *Environ. Sci. Technol.*, vol. 46, no. 4, pp. 2460–2466, 2012.
- [6] E. Durusut and A. Mattos, “Industrial carbon capture business models (Element Energy Ltd. for BEIS),” 2018.

## TOPIC 2: The Role of CCS in Enabling Clean Hydrogen

The 18 session participants (see Appendix 1) were divided in three teams. All teams addressed the three main questions that are given in bold below.

Below follow the outcomes of discussions.

### **Which opportunities are identified from an industrial point of view?**

The overarching driver is the quest for a low-carbon society. Although the regulatory framework is at this moment is not sufficient to make sure that CO<sub>2</sub> emissions will decrease to net-zero, an increasing number of governments announce 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, ...)
- High temperature heat
- Industry (reducing agent in steel, feedstock in refineries and other chemical industry)
- Energy storage

Presently, and most likely for next 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 opens more opportunities:

- Production of hydrogen and carbon black and store the solid carbon
- Finding applications also for the CO<sub>2</sub>. Examples are EOR and combination of H<sub>2</sub> and CO<sub>2</sub> in CCU
- Spiking natural gas with hydrogen for transport through existing in pipelines
- Achieving negative emissions by gasification of biomass and subsequent hydrogen production with CCS, assuming the biomass meets sustainability criteria

Avoiding transportation of CO<sub>2</sub> across borders (i.e. avoid restrictions imposed by the London Protocol), by either do reforming where the gas is produced, store the CO<sub>2</sub> there and transport hydrogen, transport the natural gas, and reform and store CO<sub>2</sub> in receiving country. Finally, hydrogen produced with hydrocarbons and CCS offers the additional opportunities that

- Re-use of the existing and extensive infrastructure developed for natural gas distribution
- Drawing on extensive competence in industry, research organisations and academia

Examples of projects that see the opportunities mentioned by the participants are H21 in UK and Magnum and H-Vision (Rotterdam) in Netherlands.

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

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

Here the teams drew on a graph by M. Hekkert, Netherlands (Appendix 2), 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 identified that will be needed to get from research to commercial product were (not necessarily in order of importance):

- Thinking the whole value chain and do value chain demonstrations. This builds confidence, opens for mastering complexities, will inform choices, and contributes to build market confidence.
  - May result in change from market pull to market push, and will increase public acceptance

- To include commonalities for hydrogen regardless of production methods (compression, storage, transport and infrastructure)
- Go for large-scale: allows for impact and well-informed decisions, de-risking technology
- Demonstration project TRL 7-9. These projects must have a viable business case after project ends
- Go for small-scale: gives room for experiments, allows quick decisions and niches, for example connected to biogas production.
- Start with the “low-hanging fruits”, e.g. the H<sub>2</sub>/CO<sub>2</sub> from the reforming process
- Academia should inform discussions
- ‘Middlemen’ are needed to link the chain between different stakeholders; can suggest opportunities and create industrial symbiosis
- Sharing knowledge, data and other relevant information (policies, permitting etc)
- In absence of effective CO<sub>2</sub> regulation or an effective price for CO<sub>2</sub> emission - Government funding – consistent in time – and international level playing field
- International cooperation on test centre to avoid duplications, ‘TCM for hydrogen’, joint funding as well as use
- Regulation to mandate low carbon content

More specifically, some R&D activities were identified:

- Increasing capture rate without increasing cost
- Understanding energy requirement, purity of CO<sub>2</sub>, liquefaction CO<sub>2</sub> etc.
- Reducing cost of low carbon H<sub>2</sub> production, e.g. further developing sorbent enhanced reforming
- Process intensification (e.g. vacuum pressure swing absorption, ELEGANCY project)
- Opportunity for energy storage, H<sub>2</sub> or NH<sub>3</sub>
- Public acceptance

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

- Encouraging international collaboration and joint industry projects where several industrial players can share cost of e.g. demonstration size projects
- Creating a vibrant market for technology vendors
- Encouraging industry clusters, where different industrial sectors join around hubs with large-scale hydrogen production with CCS and a common infrastructure. An example, based on a Dutch case, is included in Appendix 3.
- Encouraging public-private partnerships
- Supporting policies and regulations for use of H<sub>2</sub> produced with CO<sub>2</sub> capture
- Being honest about safety aspects of H<sub>2</sub>

### TOPIC 3: Storage and CO<sub>2</sub> Networks

The participants at this parallel session at the Mission Innovation CCUS Workshop in Trondheim were divided in four teams. All teams addressed the three main questions that are given in bold below. The outcomes were presented at the plenary session at the end of the workshop and are summarised below.

#### **Which opportunities are identified from an industrial point of view?**

CO<sub>2</sub> 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<sub>2</sub> transport and storage technologies:

- Large-scale CO<sub>2</sub> storage will create an enormous business potential: the technical know-how is there to get started, young people are motivated to work on green topics, there are opportunities for new business/companies including independent assessment bodies, and there are opportunities for added-value complementary activities (water production, EOR, energy production and storage,...).
- Cost-effective CO<sub>2</sub> storage and transport hub systems can be developed: a cluster approach by geographical areas, with a portfolio of storage sites connected to CO<sub>2</sub>-emitting plants, reduces the risks and the costs while allowing tailored solutions to local contexts.
- The digital revolution (big data, machine learning, artificial intelligence) applied to CO<sub>2</sub> 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.
- The three above points should contribute to better address the perception issue on CO<sub>2</sub> storage, which still exists among the public authorities and the general public. It is important to further develop methods for quantifying project risks and benefits, and for mitigating unexpected events. Besides site performance risks, economical and market failure risks, as well as public perception risks have to be addressed.

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

Several recommendations are made:

- Pilots, demos and real projects (i.e. projects at scale beyond lab) are needed for field-testing and technology development in real conditions. They will have also a key public perception role, enabling local consultation and local 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, network & hubs planning tools. This requires most of the time pilots and demos, and application in full-scale projects.
- An international cooperative project that could be named « Earth Geonome project » could be created, according to a model similar to other famous scientific initiatives (e.g. Earth Biogenome Project, Integrated Ocean Drilling Program, International Space station). This cooperative project with many participating countries and companies could boost national mapping of CO<sub>2</sub> storage resources and address topics too expensive to be addressed for each participant alone, e.g. providing a big international test site.

- Mission Innovation Twinning projects could be created, in which two or more countries work together on specific projects (technology development, pilot & demonstration). Twinning of countries with CCS experience with e.g. developing countries would facilitate global dissemination of CCS.
- Transparency and openness is key. This includes sharing of data and results from all the technology development steps. This also includes a proactive communication on risks and mitigation actions, balanced with information on benefits (take the example of NASA's approach).
- Regulatory rules have to be set up. This will facilitate the path to commercialization of CO<sub>2</sub> 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<sub>2</sub> storage and transport networks at national level. Key joint activities could include:

- Data sharing and using 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 (e.g. tax).
- A Mission Innovation Platform for sharing stories, knowledge and case studies could be created. This would enable a better and wider use of existing technical knowledge. This would also facilitate public communication and risk quantification.
- Maturation of an international certification process for bankable CO<sub>2</sub> storage resource would be advantageous. 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<sub>2</sub> storage and transport networks. Future work can build on the practical approach currently being developed to maturing CO<sub>2</sub> Storage Readiness Levels (SRLs) and on the CO<sub>2</sub> Storage Resource Management System framework (SRMS) for resource reporting, which is similar to systems for classification of petroleum resources.
- One (or several) internationally recognized CO<sub>2</sub> storage software could be established, as done with climate models. They should be open source. 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 the financial communities is needed for building confidence in CO<sub>2</sub> storage, managing the risks, incentivizing implementation of CO<sub>2</sub> storage and transport networks, and penalizing if promises are not reached.
- Stronger engagement with the public authorities of each Mission Innovation country is needed so that they are aware of this carbon sink technology and can decide to include it in their revised Nationally Determined Contributions (NDCs) and strategies to mitigate climate change.

## TOPIC 4: Storage Monitoring

**Introduction:** This document summarizes the outcomes of the Carbon Capture Utilization and CCUS Experts' Workshop held June 19-20, 2019 in Trondheim, Norway. The overarching goal of the workshop was to further address the challenges outlined in the Carbon Capture Innovation Challenge report of the September 2017 Mission Innovation CCUS Experts Workshop. The subarea of focus reported herein is Topic 4: The Storage Panel Report on Monitoring Verification and Performance Metrics.

The challenges addressed include: 1) Monitoring to demonstrate containment and enable site closure: transforming far-field monitoring with new tools to directly measure state variables, 2) Smart monitoring in the far-field, 3) Improving methodologies for monitoring plans, 4) Improving interpretation and use of large, complex data sets, and 5) Assessing anomalies and providing assurance – location, attribution, quantification. The challenges were viewed within the context of upscaling CCUS, which may require projects to operate in close proximity. 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 aspects important and applicable to all areas of monitoring and were therefore be 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 which are critical to long-term subsurface CO<sub>2</sub> containment, and this topic was therefore 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, collaborations among industry and research entities on international projects, and sharing data. Producing useable outcomes from large data sets was also identified across all groups, with a suggestion to look at artificial intelligence and how other industries (e.g. the medical industry) manage their large data sets. Co-operative “learning-by-doing” activities were consistently described as important towards driving 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 thoroughly test and trial tools to eliminate all uncertainties. In short, learning through international collaborations on projects that put CO<sub>2</sub> into the ground, especially in the 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, largely 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 in tool choice and application as well as in developing flexible and staged monitoring workflows. Digital “twins” or

replicas of projects could be used to explore unlikely scenarios without causing public confusion regarding CO<sub>2</sub> 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) at scale, among projects, would provide critical information for evaluating 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 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. 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 the establishment of a centralized team to advise/intervene when needed and the formation of an advisory “peer-review” panel to help “certifying” CCS projects.

## TOPIC 5: Going Climate Positive

This session dealt with what is commonly described as carbon negative technologies or CO<sub>2</sub> removal technologies. The need for these solutions has become evident as emissions from agriculture (non-CO<sub>2</sub> gases) and various process emissions are hard or unavoidable thus net GHG removal technologies are needed.

Such technologies have been identified in various recent reports (Royal Society, Akatech) and span from mineralization via weathering of minerals to bioCCS and direct air capture (DAC). These technologies provide nothing else than removal of greenhouse gases and as such has a significant market introduction barrier. Further on, they are 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 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 sources sustainably and that should always be assessed by proper 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% - thus providing net removal of CO<sub>2</sub> 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<sub>2</sub> from the air at competitive prices to commercial CO<sub>2</sub>. 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 3 routes for capturing CO<sub>2</sub> being known as post-combustion, pre-combustion and oxy-fuel can all be employed for biomass too.
- Negative emission technologies need policy & incentives.
- Fuels production can be commercial bridge to advance negative emission technologies- the question about time and urgency on the other hand 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 challenge.
- Huge demand on terrestrial biomass sources, land use issues. Would need to be sustainable, otherwise creates other negative environmental issues. Friction with Sustainable Development Goals.
- Challenge: full carbon accounting not fully understood and agreed upon. Solutions may be locally different.
- 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 first commercially viable plants (municipal waste, pulp & paper)
- Modular capture plants for small scale application at town level- especially feasible for waste to energy plants
- 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 R&I agenda for GHG removal technologies at large- also extending beyond using CCS. These cover for instance 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.

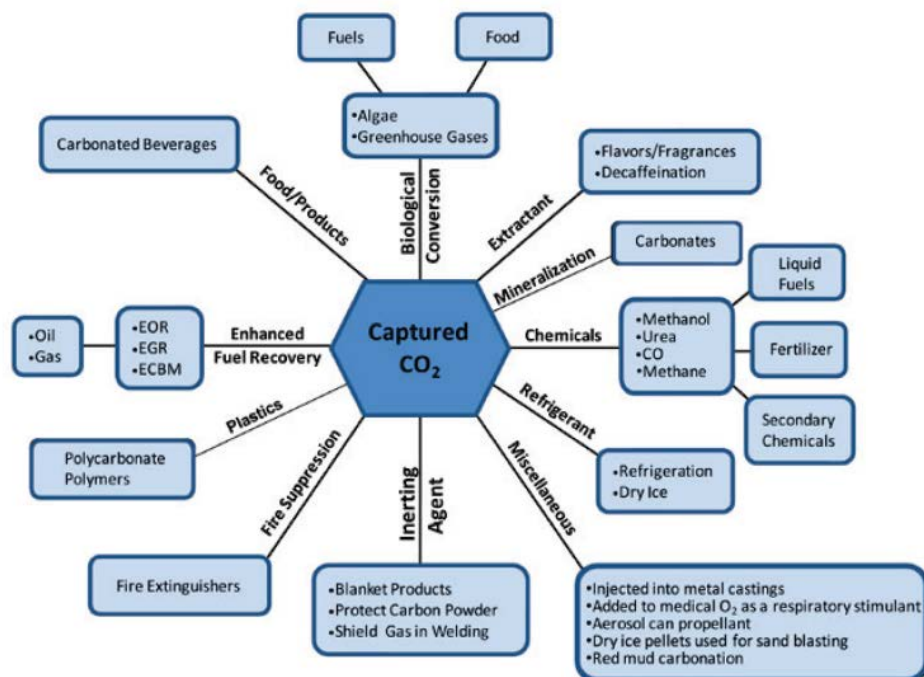
- It is thus both mature and early days for climate positive solutions. What is clear is that the terrestrial sources of biomass for curbing climate change are limited and very soon get in conflict with food production storing CO<sub>2</sub> in trees, water usage and transportation issues. Each value chain has to be investigated to ensure sustainability.
- 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 (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<sub>2</sub> 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<sub>2</sub> capture and sequestration part later)
- Address remaining technology challenges for conversion of trees (e.g. in CA) 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.
- Tie large commercial projects and products to further development.
- 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).

Thus, we need a global resource stocktake (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?**

- We need to talk more about "climate positive solutions", rather than carbon negative solutions or reducing CO<sub>2</sub> emissions. See example of public acceptance of direct air capture. Has apparently a workable business model.
- Need for more unified effort to develop more climate positive solutions. Mobilize international efforts.
- Need to integrate value chains. Cheap modularized capture plants (e.g. Aker solutions). Still need CO<sub>2</sub> infrastructure.
- Importance of knowledge sharing and standardization, best practices
- Leverage R&I co-operation – global broker for climate positive solutions- accounting principles.
- Cost of carbon consumption and scaling up need to be reflected
- Leveraging and managing 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)

## TOPIC 6: CO<sub>2</sub> Utilization



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

CO<sub>2</sub> utilisation topic was discussed within 4 sub-topical groups: fuels/chemicals/plastics, mineralization/building materials, CO<sub>2</sub>-Enhanced oil recovery (EOR) and a transverse sub-topic aiming at investigating market/thermodynamics of CCU routes in general.

Participants on average reckoned most CCU routes, compared to CCS, do not provide massive decarbonisation pathways as CO<sub>2</sub> will be released once more into the atmosphere on a short-medium term basis.

### Opportunities identified from an industrial point of view

Competitive advantage varies from CCU routes. Several studies identified market opportunities for CCU routes. Different market's size showed opportunities for all CCU routes from niches to large size. The update of these studies should be undertaken taking in account the market's evolution. CCU has a better public acceptance contrary to CCS. It 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 such as in air transportation and marine sector, CO<sub>2</sub>-based products might be considered among the best options.

On the other hand, as O&G production is set to decline, CO<sub>2</sub>-EOR is offering GHG emission reduction during energy transition while being already a proven technology at commercial scale albeit mainly in the US. One its main advantage is the potential reuse of existing facilities (wells, infrastructure, ...) to demonstrate CO<sub>2</sub> storage at large scale.

Mineralization is singled out as the main opportunity for utilization as far as market size is concerned. It also has the benefit to provide the market with a CCU substitute which does not disrupt the conventional one. In addition, new CCU mineralisation plant could fit nicely within the proximity of industries which would provide CO<sub>2</sub> streams and material for the construction and civil works i.e. 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 technico-economic assessment (TEA) are requested to identify the most promising CCU routes. Boundaries of these studies are as important as the life cycle of the technologies. A specific attention to the potential of GHG reduction shall be addressed when different H<sub>2</sub> sources or CO<sub>2</sub> feedstock are considered.

Again, depending on which sub-topic, there are several lessons learned which could be highlighted: polymers count a few success stories from research to commercial scale but remains case specific. Research much aim at focusing on CO<sub>2</sub> based chemicals which requires less modifications as a first step. In the mineralisation/ 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<sub>2</sub>. Conversely, as technology is already proven, and deployed at commercial scale, only low TRL should be considered to improve CO<sub>2</sub>-EOR process technologies aiming at sustainability encompassing 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. For the years to come CO<sub>2</sub> will be available in large amount. Without higher efficiency in capture, the cost for using or storing CO<sub>2</sub> may be too high. It will remain one of the main priority research area, especially new processes with high energy efficiency, 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<sub>2</sub> based products have higher cost compare to fossil-based products. CCU needs primarily joint action in the field of legislation: mechanisms should be set up by governments as CO<sub>2</sub> tax or other regulations. Related to the potential of its GHG emission reduction, incentive for this kind of technologies should be questioned because their potential of mitigation still need to be demonstrated. For some CCU pathways, it is currently considered as limited. Nevertheless, there are ample activities which can be undertaken within joint action.

In particular, within mineralization and building materials sub-topic, join activity to set up label to differentiate the benefice of the sequestration time of CO<sub>2</sub> in CO<sub>2</sub> based products should be encouraged. Along with time, any volume given to a technology which will enable CO<sub>2</sub> sequestration should also be included in the label. This will provide the magnitude for potential GHG emission reduction. Based on this labelling, incentives should be designed as tax credit because mineralisation is achieved at higher energy costs.

Legislation issue could also be addressed within international partnerships. In some countries, legislation is a hurdle for the development of carbonatation using waste materials: for instance, in France and Germany regulation prevent waste material from being used as based 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 particular case of CO<sub>2</sub>-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, during a transitional period, its potential for GHG emission reduction. This could be achieved through international collaboration on establishing a standard, ensuring anthropogenic CO<sub>2</sub> is used for enhanced oil recovery rather than natural CO<sub>2</sub> extracted from subsurface. In addition, low TRL research requires international collaboration.