Mission Innovation Challenge CCUS

Workshop Summaries

June 19-20
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_2 networks
4. Storage monitoring
5. Going climate positive
6. CO_2 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. (Summary from Topic 3 will be added during the summer, well ahead of the September 6 deadline).

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_2-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_2 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_2-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 Zweigel
- 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_2 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_2 utilization

- Chair: **Paul Bonnetblanc**, Ministry of Ecological Solidarity Transition
- Secretary: **Aicha El Khamlichi**, 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_2 emissions from fossil fuel combustion and, under the IEA ETP B2DS, those must be reduced by 40% in 2050[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 the total 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 sectors 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], covering the intermittency of renewables and offering a cheaper decarbonising solution[2]
- 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_2 concentration in the gas streams in power plants can be beneficial to capture of the CO_2. Specific EIIs emit gas streams with higher CO_2 concentration than those in power plants, which could further reduce the CO_2 capture cost. EIIs emit CO_2 directly or indirectly through burning fossil fuels for energy supply, but some EIIs inherently 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 [2], and thus those EIIS cannot be decarbonised without CCUS.
- The implementation of BECCS (Bio-Energy with CCS) offers a deeper CO_2 emissions reduction in power plants and EIIs, with the opportunity to reach negative or net-zero emissions scenarios at reasonable cost [3].
- 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[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_2 capture costs and/or help on achieving specific emissions goals [4]
- 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[5]
- CO_2 utilization (within a CCU or CCUS structure) can offer an additional source of revenue
- EIIs 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 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.

[1] Compared to the Reference Technology Scenario (RTS). Source: https://www.iea.org/etp/explore/
[2] 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_2 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_2 value products and encouraging the consumers to buy low CO_2 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_X and deNO_X processes)
- EIIs 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 EIIs, 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_2 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_2stCAP - Cutting Cost of CO_2 Capture in Process Industry," *Energy Procedia*, vol. 114, no. 1876, pp. 6303–6315, 2017.

[5] N. Rodríguez, R. Murillo, and J. C. Abanades, "CO2capture 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.

Q1: 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_2 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_2. Examples are EOR and combination of H_2 and CO_2 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_2 across borders (i.e. avoid restrictions imposed by the London Protocol), by either do reforming where the gas is produced, store the CO_2 there and transport hydrogen, transport the natural gas, and reform and store CO_2 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.

Q2. 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_2/CO_2 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_2 regulation or an effective price for CO_2 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_2, liquefaction CO_2 etc.
- Reducing 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

Q3. 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_2 produced with CO_2 capture
- Being honest about safety aspects of H_2

TOPIC 3: Storage and CO_2 Networks

(will be added during summer)

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_2 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_2 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_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) 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_2 removal technologies. The need for these solutions has become evident as emissions from agriculture (non-CO_2 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_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 3 routes for capturing CO_2 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.

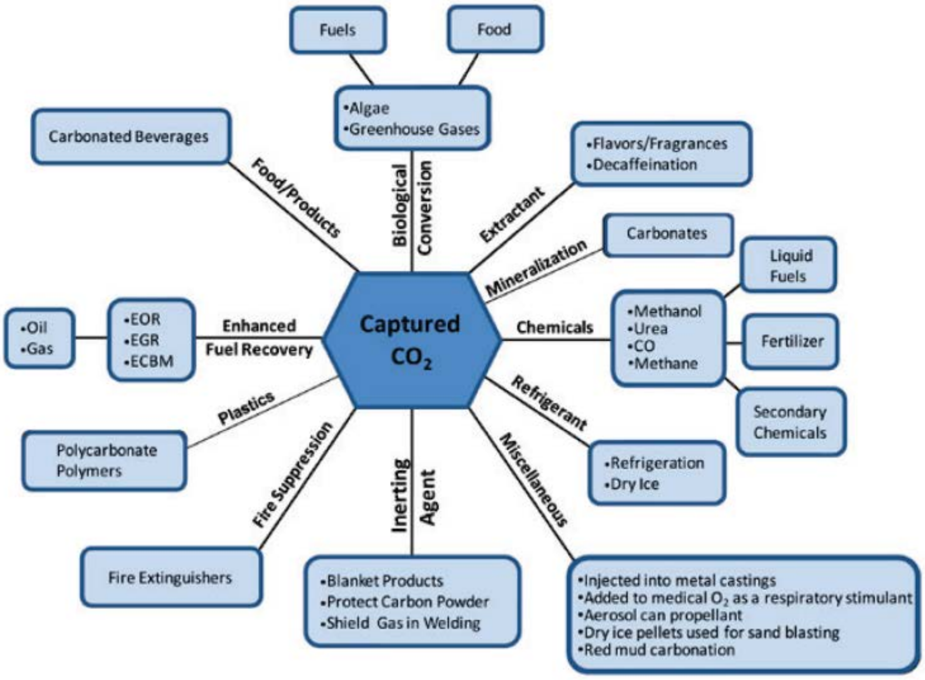
- It is thus both mature and early days for climate positive solutions. What is clear is that the terrestrial sources of biomass for curbing climate change are limited and very soon get in conflict with food production storing CO_2 in trees, water usage and transportation issues. Each value chain has 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_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 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_2 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_2 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_2 Utilization



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

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.

Participants on average reckoned most CCU routes, compared to CCS, do not provide massive decarbonisation pathways as CO_2 will be released once more into the atmosphere on a short-medium term basis.

1- 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_2-based products might be considered among the best options.

On the other hand, as O&G production is set to decline, CO_2-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_2 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_2 streams and material for the construction and civil works i.e. steel and glass.

2- 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_2 sources or CO_2 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_2 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_2. Conversely, as technology is already proven, and deployed at commercial scale, only low TRL should be considered to improve CO_2-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_2 will be available in large amount. 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 area, especially new processes with high energy efficiency, to drive the product to the market:

Thermodynamics need to be tackled for most CCU routes.

3- 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 compare to fossil-based products. CCU needs primarily joint action in the field of legislation: mechanisms should be set up by governments as CO2 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_2 in CO_2 based products should be encouraged. Along with time, any volume given to a technology which will enable CO_2 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_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, during a transitional period, its potential for GHG emission reduction. This could be achieved through international collaboration on establishing a standard, ensuring anthropogenic CO_2 is used for enhanced oil recovery rather than natural CO_2 extracted from subsurface. In additional, low TRL research requires international collaboration.