Technology Collaboration Programme
by IEA

Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Review
2022-TR04
August 2022

Carbon Dioxide Removal (CDR) Workshop, Bergen, Norway, 28th June 2022

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 30 member countries and beyond. Within its mandate, the IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics. To date, there are 38 TCPs who carry out a wide range of activities on energy technology and related issues.

ACKNOWLEDGEMENTS AND CITATIONS

This report describes a review of the Carbon Dioxide Removal (CDR) Workshop which was held in Bergen, Norway, 28th June 2022. This report was prepared by Lars Ingolf Eide (CLIMIT) and Jasmin Kemper (IEAGHG).

The report should be cited in literature as follows: 'IEAGHG, "Carbon Dioxide Removal (CDR) Workshop, Bergen, Norway, 28th June 2022", 2022-TR04, August 2022.'

Further information or copies of the report can be obtained by contacting IEAGHG at:
IEAGHG, Pure Offices, Cheltenham Office Park
Hatherley Lane, Cheltenham,
GLOS., GL51 6SH, UK

Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org
Internet: www.ieaghg.org

WORKSHOP CARBON DIOXIDE REMOVAL (CDR), BERGEN, NORWAY JUNE 28TH 2022

EXECUTIVE SUMMARY AND RECOMMENDATIONS

Reports from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), have shown that Carbon Dioxide Removal (CDR) will be required to achieve net negative emissions to reach the target of the Paris Agreement, limiting the temperature increase caused by anthropogenic greenhouse gas (GHG) emissions to 1.5°C above pre-industrial levels.

On June 28, 2022, the Carbon Sequestration Leadership Forum Technical Group(CSLF TG)
Clean Energy Ministerial (CEM) CCUS Initiative, IEAGHG, and the Mission Innovation (MI) CDR Mission jointly organized a workshop on CDR, hosted by the Research Council of Norway in Bergen, Norway.

The aim of the workshop was to provide members and other stakeholders with an update on the status of CDR, identify crucial knowledge gaps and the mechanisms to resolve them, and find possible cooperation/collaboration opportunities.

The session on Government and Policy Frameworks had speakers from the US Department of Energy (DOE), the International Panel non Clinmte Change (IPCC) and the Mission Innovation (MI) CDR Mission. Important outcomes were:

- US makes more than USD 3.5bn for DACCS projects available
- IPCC emphasises the essential role for CDR, including CCUS, in reaching net zero
- MI CDR Challenge underway with the production of a Technology Roadmap and an Action Plan.

Keynote talks included a general overview of CDR solutions and more specific presentation on the CDR solutions Direct Air Capturer (DAC), Mineralization and Bioenergy with CCS (BECCS). Key message include:

- High quality, i.e. permanent, carbon offsets/removal are needed
- Current DACCS costs tend to be high but significant cost reductions can be realised
- EM progress is slow, suffering from low TRL, lack of business cases and wider LCAs
- BECCS work scientifically as a climate mitigation pathway, but the impact will be case and service specific.

After the general introductions to CDR technologies, providers and users of the technologies presented snapshot views. Providers were represented by Mineral Carbonation International (MCi)and Climeworks, whereas the UK power utility Drax and the Norwegian waste-to-energy plant Celsio represented users of CDR. Conclusions are that

- CDR technology providers are ready to deliver and scale up

- Users are ready to implement but regulations and accounting systems must be developed.

The workshop included a panel debate on CDR accounting, with participants that have experience from Life Cycle Assessmen (LCA), emissions accounting, both in general and on BECCS and waste-to-energy in particular, as well as from regulatory work. Important outcomes are

- International cooperation and knowledge sharing is needed
- Life cycle perspectives are needed, including energy, land and water use and potential trade-offs with sustainable development targets
- Standards of monitoring, verification and reporting and for Life Cycle and Techno-economic Assessments are needed
- RD&D is needed to get costs and energy requirements down
- Nations need CDR strategies.

The workshop ended with group work, in which groups were asked to address questions to key technical roadblocks with the CDR technologies, most urgent research areas to move ahead, how market measures van create demand for CDR technologies, services and products, interesting business models that CDR projects/companies could employ, key policy / incentive drivers that governments should consider putting in place, and key issues and solutions as regards useful/helpful accounting frameworks for CDR.

The key outcomes from the workshop were:

- **The need for CDR is clearly demonstrated, emphasised e.g. by the IPCC**
- **There is the need to reduce emissions to maximum, in addition to removal (removal not panacea)**
- **Government attention and investment in CDRs is increasing: project funding announcements, deployment targets, Mission Innovation work etc.**
- **Several CDR technology options exist → all are required**
- **Companies are advancing with REAL project development and investment → this commitment is highly commendable**
- **Companies willing to buy offsets from CDR have experienced issues shortages of credits Accounting and MRV frameworks: international consistency (and convergence?) required, on various reporting frameworks including at the national level by the IPCC GHG Inventory Guidelines, on definitions of what is negative emission and recognising voluntary vs compliance markets**

Recommendations for further action

- **An international CDR collaborative club of countries could be formed, to accelerate the building of 1-5 ktpa pilots ("Orcas") in several countries → to be further discussed!**

BACKGROUND AND AIM OF WORKSHOP

Reports from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), have shown that Carbon Dioxide Removal (CDR) will be required to achieve net negative emissions to reach the target of the Paris Agreement, limiting the temperature increase caused by anthropogenic greenhouse gas (GHG) emissions to 1.5°C above pre-industrial levels.

According to IPCC's Sixth Assessment Report (AR6), CDR can serve multiple roles in the near-, mid-, and long-terms:

1) As a complement to decarbonatization efforts by further reducing net greenhouse gas (GHG) emission levels in the near-term

2) As a compensation for GHG emissions from the sectors that are the hardest to decarbonize (e.g., industry and agriculture) in the mid-term

3) As a tool to address legacy emissions by achieving and sustaining net negative GHG emissions in the long-term

CDR approaches come in many forms, from purely nature-based to engineered approaches, and some combine elements of the two. Subsets include biomass from agriculture, forestry and marine biomass, often called Biomass Carbon Removal and Storage (BiCRS), ocean chemistry, mineralization, or Direct Air Capture (DAC). Many mechanisms of removal are not well understood, and quantification of actual removal, economics and potential side-effects and trade-offs are needed.

The aim of the workshop was to provide members and other stakeholders with an update on the status of CDR, identify crucial knowledge gaps and the mechanisms to resolve them, and find possible cooperation/collaboration opportunities.

ORGANISATION OF THE WORKSHOP

The workshop was a collaboration between the following international organisations within the Carbon Capture, Utlilisation and Storage (CCUS) community:

Carbon Sequestration Leadership Forum Technical Group (CSLF TG)
Clean Energy Ministerial (CEM) CCUS Initiative
IEAGHG
Mission Innovation (MI) CDR Mission

The practical organisation and logistics were handled by the Research Council of Norway, with strong financial support from the Norwegian CLIMIT Programme.

The programme committee had the following members:

Eric Tenthorey, Geoscience Australia (CSLF TG), Chair; Mark Ackiewicz, US Department of Energy (MI CDR and CSLF TG); James Craig, IEAGHG; Tim Dixon, IEAGHG; Lars Ingolf Eide, Research Council of Norway (CSLF TG); Stephanie Hutson, US Department of Energy (CSLF TG); Jasmin Kemper, IEAGHG; Juho Lipponen, CEM CCUS; Åse Slagtern, Research Council of Norway (CSLF TG); Jørild Svalestuen, Gassnova (MI CDR).

AGENDA

CSLF Workshop on CDR
Bergen, Norway, Tuesday June 28, 2022

1) Introduction *8:30-8:45*
    a. Welcome: *Rune Volla, Research Council of Norway*
    b. Aims of workshop: *Eric Tenthorey, Geoscience Australia*

2) The Government View and Policy Frameworks *8:45-9:30 (Chair: Åse Slagtern)*
    a. US government CDR Initiatives: *Noah Deich, Dept. of Energy*
    b. CDR in the IPCC Work: *Jim Skea, Imperial College London*
    c. The Mission Innovation Role and Roadmap: *Mark Ackiewicz, Dept. of Energy*

3) Keynote Speaker Session *9:30-11:00 (Chair: Jasmin Kemper)*
    a. Introduction to CDR Technologies: *Jasmin Kemper, IEAGHG*
    b. Direct Air Capture: *Yorukcan Erbay, ElementEnergy*
    c. Mineralisation: *Ron Zevenhoven, Åbo Akademi University*
    d. BECCS: *Piera Patrizio, Imperial College London (Presented by Niall MacDowell, Imperial College)*

4) Break *11:00-11:30*

5) CDR Snapshots from Technology providers and users *11:30-12:30 (Chair: Lars Ingolf Eide)*
    a. *Mineral Carbonation International: Sophia Hamblin Wang*
    b. *Drax: Karl Smyth*
    c. *Climeworks: Louis Uzor*
    d. *Celsio: Bjerkas Jannicke*

6) Lunch *12:30-2 pm*

7) Panel session -*What is CDR and how to make good accounting? 2:00-3:15 (Chair: Tim Dixon)*
    a. Life Cycle Assessment: *Andrea Ramirez, TU Delft*
    b. Emissions Accounting: *Paul Zakkour, Carbon Counts*
    c. BECCS: *Kenneth Möllersten, IVL Swedish Environmental Research Institute*
    d. Net Negative Industries: *Jannicke Bjerkås, Celsio*
    e. Regulatory Frameworks: Ingvild Ombudstvedt, IOM Law

8) Audience working groups *3:15-4:45 (Juho Lipponen, Eric Tenthorey)*
    a. Introduction to group exercise
    b. Groups break away.
    c. Groups report back and audience discussion

9) Break + Summary of Outcomes and Close of Workshop *4:45-5:15 (Tim Dixon)*

The presentations are available from the CSLF web site.

INTRODUCTION

Key points

- **Persistent research, development and demonstration is necessary to get full scale CCS projects going**

Rune Volla, director of energy in the Research Council of Norway, wished the participants, both in person and remotely, welcome on behalf of Norway and the Research Council. The Norwegian Government has ambitious goals for deployment of CCS and want to address technology development as well as to reduce costs.

Initiatives by the Norwegian government cover the whole development chain from research, through development and demonstration to large scale CCS chain and international cooperation. The government provides public funding and encourage close cooperation with industrial actors.

Norway has and is prepared to continue contributing to joint European research efforts.

Eric Tenthorey wished the participants welcome on behalf of the organizing group, stated the aims of the workshop and encouraged all to contribute.

Eric Tenthorey, chair of the organising committee, opened the workshop (Photo: Sophia Hamblin Wang)

THE GOVERNMENT VIEW AND POLICY FRAMEWORKS

Key points

- **US makes more than USD 3.5bn for DACCS projects available**
- **IPCC emphasises the essential role for CDR, including CCUS, in reaching net zero**
- **MI CDR Challenge underway with the production of a Technology Roadmap and an Action Plan**

Noah Deich (US DOE) provided an overview of the US government CDR activities. The US carbon removal strategy tries to be not monolithic, pathway-neutral, and not seeking a specific silver bullet. Instead, the aim is to figure out which carbon removal pathways can get us to net zero most effectively. For this, not just the technical aspects but also the impacts on communities and the environment need to be considered.

The Bipartisan Infrastructure Law includes CDR, and the US has a USD 100m DAC prize in development plus USD 3.5bn to spend on four Mt CO_2 -scale DACCS projects. Noah emphasised that in the global picture this is just a fraction of what is needed, as we need 100s to 1000s of these projects, so international collaboration is crucial.

Next, Jim Skea (Imperial College London/IPCC WGIII Co-Chair) gave an overview about how CDR fares in the recent Working Group III (WGIII) contribution to the IPCC's 6th Assessment Report (AR6) "Climate Change 2022: Mitigation of Climate Change". CDR and CCS received a lot more emphasis in this than in previous IPCC reports (CDR is addressed in chapters 3, 6, 11, and 12).

One of the key messages is that it is absolutely essential to deploy CDR to reach net zero, as it is needed to counterbalance hard-to-abate emissions and to draw down CO_2 from the atmosphere in the case of temperature overshoot. However, new CDR methods still require proof-of-concept, RD&D and agreed methods for monitoring, reporting and verification (MRV).

The report also notes that:

- There are currently 28 commercially operating CCUS facilities with a combined 40 Mt CO_2 /a, the majority in industrial applications;
- The public is largely unfamiliar with carbon capture and in general support for CCS technologies is low;
- New investments in coal-fired electricity without CCS are inconsistent with < 2^{o} C;
- CCS can allow fossil fuels to be used longer, reducing stranded assets;
- Some post combustion capture (PCC) approaches are technologically ready for full scale deployment, and several 2G and 3G technologies are being developed;
- The theoretical global geological storage potential is about 10,000 Gt CO_2, of which not all is usable but still more than enough for the requirement through 2100 to limit warming to 1.5^{o} C;
- Carbon capture costs remain higher than USD 50/t CO_2 but costs can be lower for EOR cases and for CCUS clusters;
- Deep reduction of cement process emissions and some chemical processes will rely on the availability of CCS

Jim also mentioned the asymmetry between emissions and reductions/removals, and the importance of durability of the carbon storage, which can be affected by potential reversals.

Mark Ackiewicz (US DOE) provided an update on the Mission Innovation (MI) CDR Challenge, Technology Roadmap and Action Plan. The scope includes DAC, enhanced mineralisation (EM) and biomass carbon removal and storage (BiCRS), with an emphasis on secure CO_2 storage and conversion into long-lived products. Specific activities related to this include: life cycle assessments (LCAs), techno-economic assessments (TEAs), MRVs, RD&D, and the lessons learned from 1G projects.

Several technology challenges and gaps were identified for each CDR method in the scope:

- DAC: CO_2 capture capacity, CO_2 capture and desorption, energy use, material scale up
- BiCRS: biomass feedstocks, biomass conversion, CO_2 capture, utilisation, system & logistics
- EM: mineralisation kinetics, energy & land use & environmental impacts, monitoring C uptake, systems analysis

The next steps are to continue the stakeholder engagement, which includes private sector actors and international initiatives, and to finalise materials for the Global Clean Energy Action Forum in September 2022 in Pittsburgh.

Mark also highlighted that the MI CDR Challenge is clearly focussed on the technological side but some policy-oriented questions will also be considered. However, no policy recommendations will be produced.

KEYNOTE SPEAKERS

Key points

- **High quality, i.e. permanent, carbon offsets/removal are needed**
- **Current DACCS costs tend to be high but significant cost reductions can be realised**
- **EM progress is slow, suffering from low TRL, lack of business cases and wider LCAs**
- **BECCS work scientifically as a climate mitigation pathway, but the impact will be case and service specific**

Jasmin Kemper (IEAGHG) opened the session with an overview of CDR and presented how anthropogenic emissions and different CDR methods impact the fluxes of the natural carbon cycle, i.e. how atmosphere, geosphere and land and ocean sinks react to emissions and removals.

Research has shown that CDR is still effective even under certain leakage scenarios. Scenarios with a total of 800 Gt CO_2 of negative emissions with up to 1%/a leakage rate are still favourable when it comes to the near term (in this case this means the next 400 years) atmospheric CO_2 concentrations. CO_2 peaks are slightly lower and CO2 concentrations decrease earlier/faster than in the reference scenario with no negative emissions

Regarding the rebound effects of CDR, models show that after a pulse removal to 240 ppm CO_2 in the atmosphere, the concentration increases again to 260-280 ppm over the following 20-100 years, due to the ocean and land carbon sinks reacting to the new atmospheric equilibrium by releasing carbon back to the atmosphere that they have taken up in the past.

Different CDR methods naturally have different technical maturity, costs, removal potential, permanence, reversal risks, earth system feedbacks and side effects (i.e. co-benefits and trade-offs).

In CDR discussions, it is important to be clear whether we are talking about net zero or net negative and also whether we are talking about CO_2 or CO_2 equivalent (methane removals are an emerging research area).

Some of the key messages when it comes to CDR/GGR (greenhouse gas removal):

- Must not be pursued as a substitute for quick and robust action on emissions reductions;
- Must result in a permanent net reduction of atmospheric carbon;
- Must undergo case-by-case scrutiny regarding their supply chain emissions, long-term indirect emissions and potential re-emissions; and
- Must provide high quality offsets by including externalities in the certification/pricing.

These points underline the importance of robust MRV for CDR/GGR. Some methods and/or elements already have relatively established MRV while others do not, and there remain questions regarding who will take on the role of the independent auditors, cost implications and roll-out at scale.

Yorukcan Erbay (Element Energy) presented an overview of DACCS technologies (work commissioned by IEAGHG). There are two main ways to do DACCS:

- Liquid solvents, as pursued by e.g. Carbon Engineering with high temperature regeneration at 900°C. The process requires natural gas (NG) and electricity as an input. The CO_2 emissions from the oxy-fired NG calciner are captured, leading to an additional 30% of CO_2 that needs to be captured. The process benefits hugely from economies of scale as plants are large.
- Solid sorbents, as pursued by e.g. Climeworks with low temperature regeneration at 80-120° C. The process uses electricity and waste heat, is modular and benefits less from economies of scale.

Although several large scale projects are under planning, the current deployment level is only about 11 ktCO2/a; orders of magnitude less that what is needed. The largest plant is Climeworks's Orca plant in Iceland with 4 ktCO2/a, which stores the CO_2 in underground basalt rock formations. Climeworks is currently working on a plant with 10x this capacity. Other interesting projects in the pipeline are:

- Carbon Engineering's 1 Mt CO_2 /a plant in the Permian Basin (TX, USA), which is in FEED stage with construction planned to begin later in 2022. This project applies a combination of enhanced oil recovery (EOR) and dedicated geological storage;
- Carbon Engineering's 1 Mt CO_2 /a plant in Scotland as part of the Acorn project, which expected to be operational (pending government support) in late 2026;
- US DOE's USD 3.5bn for four DAC hubs with at least 1 Mt CO_2 /a capacity each.

Regarding DACCS costs:

- For first-of-a-kind (FOAK) plants: For liquids, the cost differential between smaller (100kt CO_2 /a) and larger (1 Mt CO_2 /a) plants is significant and they highly benefit from economies of scale. For solids, costs are dominated by adsorbent costs and there is room here for significant cost reductions.
- For $n^{th-}$of-a-kind (NOAK) plants: In general, costs are significantly lower and the general relationships from FOAK hold. For cases that involve the use of lower cost/free renewable energy (RE), costs go down significantly but stay above the industry target of 100 USD/t CO_2. This target can only be reached through a combination of favourable factors (i.e. very low

discount rates, situating the plant in a CCS cluster, access to low cost energy and sorbents, high learning rates).

Yorukcan also highlighted areas for further innovation:

- Innovative air contacting (e.g. passive DAC);
- Improved liquids & solids;
- Novel processes (e.g. ESA, MSA, cryogenics, crystallisation, membranes); and
- Novel business models (e.g. DAC integrated with buildings).

Ron Zevenhoven (Åbo Academy) covered enhanced mineralisation (work commissioned by IEAGHG). Most calcium on the planet is already carbonated, so not the best basis for a large scale deployment but magnesium has the potential. The chemistry involved is simple but the issue is that multiple step processes are required. The key performance indicators (KPIs) to assess mineralisation processes are: rock availability, technology readiness level (TRL), economic viability, by-products, LCA, and public acceptance.

An assessment of the 1990-2015 time period found:

- The IPCC Special Report on CCS (SRCCS) mentions the process route by Albany Research Center as a benchmark;
- A capture step is not needed and impurities usually do not play a role, so no clean-up of the used CO_2 stream is needed;
- The economic value of the products becomes a point of attention;
- LCA becomes more important but with GWP as main impact category only;
- All approaches are < TRL 5.

A more recent assessment of 2016-2021 highlights that:

- The use of mining tailings appears more often;
- Technologies are still struggling to get to TRL 5 and the literature tends to be repetitive. The majority of papers present carbonation times of days and hours when minutes are needed.
- Markets for magnesium carbonate will potentially be a bottleneck; and
- Most studies still only use GWP as the main impact category in LCAs.

There are some recent pilot scale projects, such as by Carmex (New Caledonia, France) and Mineral Carbonation International (MCI), and there seem to be some other activities in Japan, Taiwan, South Africa and Canada.

Ron finished with the following conclusions:

- There is only little reliable information (about 10 publications since 2015) available that enables one to think about > 0.1 Mt CO_2 /a mineralisation business cases;
- There is only company (MCi), who claims a TRL 6;
- The necessary mining waste availability is there (several Gt of capacity);
- A > 50 EUR/tCO2 price needed to create enough interest;
- Potential problematic/hazardous side streams need to be addressed in the LCAs.

Niall MacDowell (Imperial College London) was the last speaker in this session and gave an overview of BECCS, highlighting that biomass sits within a complex ecosystem of potential conversion and utilisation pathways.

The balance between BECCS providing an energy service and a carbon removal service is important, e.g. for bioethanol, the majority of the carbon is embedded in the biofuel and later released to the atmosphere and only a portion can be easily captured and geologically stored. In contrast, this balance shifts, e.g. for biomass gasification to produce hydrogen, where the majority of the carbon can be captured and stored. This leads to the interesting question of what the value of BECCS is and what service is valued more (heat, electricity, mobility, or carbon removal).

Regarding the carbon removal efficiency of different BECCS supply chains, there will be different amounts of carbon leakage along the supply chains depending on biomass cultivation & harvest, land use change (iLUC/LUC), pre-treatment, conversion process, capture process, biomass transportation, and CO_2 transport & storage infrastructure. For different BECCS supply chains in the UK, the removal efficiency tends to be around 70-85%.

BECCS pathways in industry are highly sensitive to the carbon intensity of electricity. When using biomass to its maximum potential, one could end up removing 0.5 t CO_2 /t steel produced, i.e. carbon negative steel production is possible. As for the impact of low carbon and low cost electricity, the answer is about how exactly BECCS pathways in the steel industry will look like will be different for different locations.

Regarding ecosystem services and energy security trade-offs, preliminary research shows it is possible to take into account all relevant impacts (biodiversity, land use, water use, wood production, removal costs, pollution etc.) and deliver a carbon removal service that is cost effective but that does not impact biodiversity significantly.

Niall summarised the following take home messages:

- Scientifically, BECCS works as a climate mitigation pathway, but the potential will be case specific;
- How it works and how well it works will be a matter of choice;
- It matters what service is targeted.

CDR SNAPSHOTS FROM TECHNOLOGY PROVIDERS AND USERS

Key points

- **CDR technology providers are ready to deliver and scale up**
- **Users are ready to implement but regulations and accounting systems must be developed**

The purpose of this section was to get some insights and perspectives of the technology providers and the users of CDR technologies. First out was Sophia Hamblin Wang of Mineral Carbonation International (MCi), an Australian based technology platform that transforms CO_2 into building materials and other valuable industrial products. She stressed what had been conveyed in previous sessions – the importance of fighting climate change and preserve the planet for future generations.

MCi focuses on mineral carbonation by converting industrial waste and ultramafic rocks into building materials and other valuable resources. Mineral carbonation occurs naturally and MCi has taken the process into pilot plant and speeding up the process from geologic time scales to minutes. The resources in the form of available rock are sufficient to lock up all carbon in from all fossil fuels available for millennia. The company has created business models for turning waste into useful products for the circular economy, and it is expanding.

The pilot plant is at TRL6 and has been operating since 2017, with three generations of technology. The plant runs continuously and produces a range of products for the building industry, including cement.

Since last year, Australia has had a CCU technology roadmap that has shown that mineral carbonation is net negative and that the feedstock is available.

MCi has won prizes, works globally and have plans for future expansion and to move up the TRL ladder.

The CDR strategy of the the large UK power utility Drax, was presented by Karl Drax. Drax launched corporate strategy and includes ambitions to be a global leader in negative emissions. Presently they have installed capacity of over 2 GW of biogenic electricity, for which they will include BECCS. The overall ambition is at least 8 Mt captured and stored biogenic CO_2 globally by 2030, therefore becoming a carbon negative company.

BECCS is important to the UK strategy to become net negative in terms of emissions. Of the 60 Mt CO2/year reductions needed by 2050, 80% will come from BECSS one way or the other. Drax will be an important player in this.

Drax is located in the Humber region of the UK and as such will be part of the East Coast Cluster and the infrastructure that is planned in the region for CO_2 transport to storage in the Endurance field off the east coast of England. The Drax Power Station has six generating units: 4 biomass units (2 earmarked for BECCS conversion by 2030) and 2 coal units that will close later this year.

Drax has the most technically advanced CCS project in the UK, building on an extensive engineering programme:

- Solvent piloting the power station since 2019
- Pre-FEED work completed by Worley in Q1 2021
- First CCS project in the UK to announce a capture technology licence agreement with Mitsubishi Heavy Industries in June 2021
- EPC partner announced as Worley in December 2021
- FEED study commenced January 2022
- Drax will spend over £40m in 2022 to progress the BECCS project, from balance sheet.
- Drax is targeting commissioning of our first BECCS unit in 2027, our second by 2029.
- FID by Q1 2024

Karl ended his talk by stating that BECCS will be needed in other jurisdictions as well.

Louis Uzor presented the company Climeworks. He started by emphasising the need for net negative emissions and elaborated a bit on the graph that was shown by several previous speakers. Climeworks has installed more than 25 DAC facilities since 2009, including the world's largest DACCS facility Orca in Iceland. The company has expanded significantly, to include more than 200 workers, 100 000 hours operational experience, obtained less than 10% life cycle emissions and secured $810 equity funding.

The Climeworks technology is a solid sorbent capture process. They cooperate with storage operators, for example mineralisation companies. Climeworks is ready to scale up. The social aspect is an important part of Climeworks' activities, and they interact with local communities. Climeworks is ready but market development and government initiatives are necessary.

Louis referred to the cost reduction wind and PV have achieved as installed capacity increases. As Climeworks can be deployed in modules and expect a fast uptake of the technology. The present ambition is to install multi-mega ton capacity by 2030.

The last speaker before lunch was Jannicke Gerner Bjerkås of the Celsio waste- to-energy plant in Oslo. The Celsio plant provides district heating to Oslo from a waste incineration plant, the largest CO2 emission source.

Celsio has ambition to be the world's first full scale WtE plant with CCS. The plant is part of the Norwegian Longship project that will take CO_2 from different sources to store it under the North Sea. The plant will capture 400 000 t CO_2 /year at 90% capture. The CO_2 will be transported to Oslo harbour by truck for shipping to the Northern Lights receiving facility on the west coast of Norway. The capture technology, provided by Shell, has been tested extensively between 2018 and 2021. The project has received funding from the city of Oslo, the Norwegian government and the owners. The project expects to come online in Q1 2026.

On a global scale, waste levels are increasing, with much in landfills that have large methane emissions and result in 20 % of global GHG emissions. As 50% of the municipal waste is of biogenic origin, this is probably valid also for other WtE faciilites, installing CCS will result in CDR and a carbon negative solution. However, proper regulations and accounting systems are lacking.

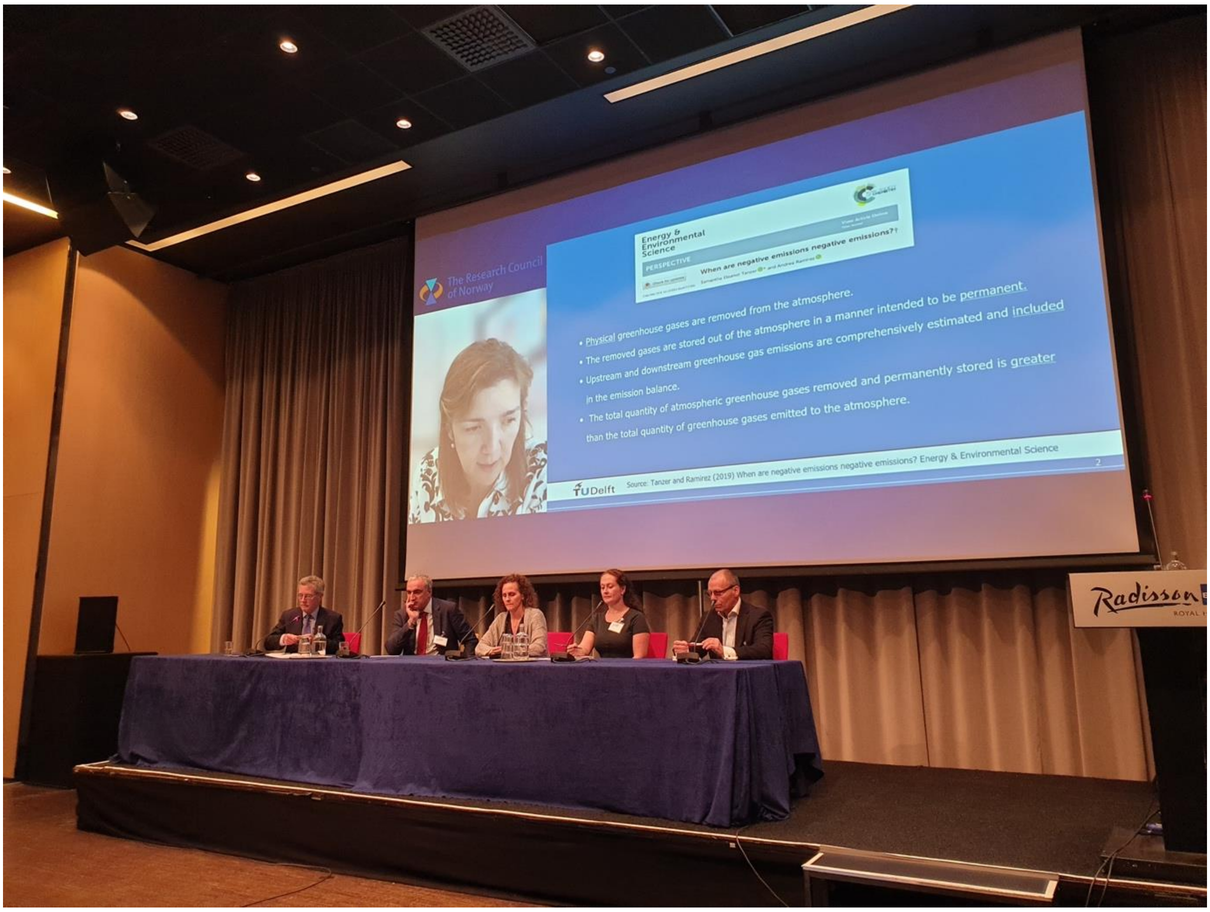
PANEL SESSION -WHAT IS CDR AND HOW TO MAKE GOOD ACCOUNTING?

Key points

- **Clear accounting methodologies for CDR are needed and accounting and crediting systems must have means in place to avoid double accounting**
- **The compliance carbon markets and countries' NDCs need the IPCC GHG Inventory Guidelines to recognise emission removals using DACCS, and the IPCC Task Force on National GHG Inventories (ITF) is encouraged to address this**
- **The voluntary carbon markets should have clear distinction between emission reductions and real net negative removals**

The panel debate was moderated by Tim Dixon, IEAGHG and the participants were

- Andrea Ramirez, TU Delft, with long experience in Life Cycle Assessments
- Paul Zakkour, Carbon Counts has done extensive work within emissions accounting;
- Kenneth Möllersten, IVL Swedish Environmental Research Institute, who has worked on accounting for BECCS for a long time;
- Jannicke Bjerkås, Celsio, with experience on accounting from the net negative industries and the waste-to-energy industry in particular; and
- Ingvild Ombudstvedt, IOM Law, a lawyer who has spent some time diving into regulatory frameworks.



Moderator Tim Dixon (far left) and panelists (from left to right) Paul Zakkour, Jannicke Bjerkås, Ingvild Ombudstevdt and Kenneth Möllersten. On the screen Andrea Ramirez, who participated remotely (Photo Eric Tenthorey).

The panelists were given a few minutes each to introduce themselves and how their topic relates to the overall question of the session.

Andrea Ramirez pointed out what is required for a CDR approach to qualify as a net negative solution and that the choice of system boundaries will have significant impact on the life cycle assessment. In her mind, temporal versus permanence is more value choice than a LCA /accounting problem. There was also a warning that recycling may not necessarily be a permanent solution.

Paul Zakkour reflected on the deep dive work Carbon Counts had done with Umwelt Bundesamt Austria, Ecologic Berlin and Ramboll for the European Commission. He emphasises the importance of proper system boundaries but also highlighted challenges with existing policies and method design, and how removals at the activity level be effectively recorded in national GHG inventories

Kenneth Möllersten explained the Swedish position on CDR. BECCS is their silver bullet. A project is underway to analyse the opportunities for a Nordic BECCS market. Kenneth sees the same challenges as Paul and a challenge is to avoid double claims. For approval of credit, a clear path towards net zero of net negative will be required, along with high quality credit approvals and that the emission reductions are not part of NDCs.

Jannicke Bjerkås again pointed to the importance of differentiating between emissions reduction and real carbon removal, as well as the question of permanence. A system should be the same for private industry as for governments, and it is needed to kick-start and lift projects. There is increasing interest for the accounting issue in private industry.

Ingvild Ombustvedt presented a proposal for a framework for accounting and trading of CDR credits (CRCs), developed on behalf of Horisont Energy. Key points include a national legislation governed by what is called the Effort Sharing Regulation (ESR), and should be based on a national register with an issuer and an auditor; sustainable CO_2 from biomass measured and certified according to RED2; mass-balance based system for CO_2 capture, transport and storage; 1 ton of sustainable CO_2 stored (net) gives 1 CRC; emission reductions in the country where the CRC is used; and unified definition of CRC's in EU allowing cross-border trading.

After the short introductory presentations, the moderator asked the panel if they see any problems related to the future inclusion of DACCS in the IPCC GHG Inventory Guidelines (CCS, BECCS and biochar are already included). The first short response was "No significant problems" but the ensuing discussion revealed that there are different opinions on this, because of the differences between the voluntary carbon markets where CDR accounting work is underway and the compliance carbon markets for which national reporting using the IPCC GHG Inventory Guidelines is needed for emissions removals to be in countries' NDCs. The main problem seems to ensuring that projects deliver real net negative emissions if using the voluntary markets, to avoid double crediting, and to have a system that secures the governments needs to achieve credits for their NDCs.

The second question to the panel was about Article 6 in the Paris Agreement and the planned work on inclusion of CDR. Will it create a problem that DACCS is not covered in the IPCC GHG Inventory Guidelines, particularly for cooperation between countries if emissions removals cannot be recognised at the national level in their inventory and NDCs? The challenge with the work on regulatory frameworks is that we try to develop the regulations with having neither the technologies nor the commercial industry quite in place yet. Development happens quickly and stakeholders want to pull in the same directions, thus progress is made. However, we still have many initiatives and systems and one question is if these can converge. Probably not, the systems and settings are diverse. However, on regionals basis it is possible, and Europe is an example.

An interesting question came from the audience: How far from a CO2 emission source must a DAC facility be before capture and emission reduction turns into removal? There are no rules on this but the question illustrates the challenge in distinguishing between emission reduction and net negative emissions.

AUDIENCE WORKING GROUPS

Key points

- **International cooperation and knowledge sharing is needed**
- **Life cycle perspectives are needed, including energy, land and water use and potential trade-offs with sustainable development targets**
- **Standards of monitoring, verification and reporting and for Life Cycle and Techno-economic Assessments are needed**
- **RD&D is needed to get costs and energy requirements down**
- **Nations need CDR strategies**

Photo Eric Tenthorey

During the last session of this workshop, the attendees split into six smaller groups. The objective was to further discuss six questions proposed by the organisers, linked to the aims of this workshop, in order to identify the next steps regarding development and deployment of CDR technologies. The questions were

For two "technology groups":

- What are the key technical roadblocks with the CDR technologies?
- What are the most urgent research areas to move ahead?

For two “Markets and business models” groups:

- How can various market measures create demand for CDR technologies, services and products?
- What might be some interesting business models that CDR projects/companies could employ?

For two “Policy questions” groups:

- What are some key policy / incentive drivers that governments should consider putting in place?
- What are the key issues and solutions as regards useful/helpful accounting frameworks for CDR?

Technology

Discussions in the technology groups included the long-term performance for DAC materials, such as stable materials under wide environmental range temperature, humidity, dust conditions; and DAC systems that reduce energy requirements and use sustainable and low carbon energy as well as low temperature waste heat. This will include improved chemicals (liquid, solid) for improved capture performance; novel approaches (e.g. moisture swing) and materials that can do both point source capture & DAC. Capability to handling impurities is important for capture technologies to be deployed in capturing biogenic CO_2 from combustion and conversion of biomass, including municipal waste and residues from pulp and paper production. The need for improved efficiency of pyrolysis technologies was pointed out.

Accelerate 1-5 kta DAC pilots integrated with sustainable storage to validate commercial ready modular components/systems is crucial for accelerating the deployment of CDR, and in particular DAC. Such small pilots are needed in more countries and require co-investment from the government.

Using salt caverns and shallow reservoirs for storage of captured CO_2 could be an alternative to deep aquifers.

There is a need to consider the whole CDR chain in a life cycle perspective, to avoid trade-offs with sustainability targets, including energy, land and water use, use of dedicated crops for BiCRS, as well as up- and downstream processes for biomass, rare metals, etc.

Better and more universal methods and procedures for monitoring, verification and reporting (MRV) will be needed for storage approaches beyond geological storage (e.g., ambient mineralization, biochar; minerals spreading). Monitoring could include remote sensing.

The discussions also touched upon CO_2 utilization approaches tailored for CDR (e.g., mineralization, reactive capture), without going into depth.

Market and business models

The groups found that the 2023 Conference of the Parties (CoP) will be an important milestone to push CDR strategies and also to include them in the next round of Nationally Determined Contributions (NDCs).

In line with the Technology groups, the Market and business models groups found that RD&D funding must be accelerated to achieve more cost reductions, and that knowledge sharing, i.e. sharing of experience from projects, policy and business model approaches, should be maximised. Industrial CO_2 hubs and shared infrastructure should be considered for CDR.

As for business models, it should be considered how "Public utility" style business model can be adapted for removals.

Policy

The groups identified a need for tailored government strategies for CDRs ("Why we do this – what our targets are – how we do this"). The strategies could include cost sharing, tax credits, carbon removal credits, financial incentives and R&D funding.

The incentives for deployment for CDR could include both carrot and stick approaches as well as investable policy approaches, something that are still lacking.

RD&D funding must be maximised to achieve cost reductions.

Also these groups identified the development of standards for Life Cycle Assessments (LCA) and Techno-Economic Assessments (TEA) as important, as well as for MVR. They pointed out that pilot projects are needed to show how MRV can work for CDR projects.

"Socialising" the technology is important. One way may be to build more "Orcas" to show the world that CDR works and can be deployed in many countries.

Finally, international cooperation and burden sharing is important for success.

SUMMARY OF OUTCOMES AND CLOSE OF WORKSHOP

The workshop was summarised by Tim Dixon, IEAGHG, and Juho Lipponen CEM CCUS, as follows:

Key points

- **The need for CDR is clearly demonstrated, emphasised e.g. by the IPCC**
- **There is the need to reduce emissions to maximum, in addition to removal (removal not panacea)**
- **Government attention and investment in CDRs is increasing: project funding announcements, deployment targets, Mission Innovation work etc.**
- **Several CDR technology options exist → all are required**
- **Companies are advancing with REAL project development and investment → this commitment is highly commendable**
- **Companies willing to buy offsets from CDR have experienced issues shortages of credits Accounting and MRV frameworks: international consistency (and convergence?) required, on various reporting frameworks including at the national level by the IPCC GHG Inventory Guidelines, on definitions of what is negative emission and recognising voluntary vs compliance markets**

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org