Evaluating technology options to mitigate greenhouse gas emissions

annualreview 2021

IEA GREENHOUSE GAS R&D PROGRAMME

Technology Collaboration Programme
by iea

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.

Further information on the IEA Greenhouse Gas R&D Programmes activities can be found at:
www.ieaghg.org

General enquiries can be made via: mail@ieaghg.org

Specific enquiries regarding IEAGHG's activities and membership can be made by writing to the General Manager at:

General Manager
IEA Greenhouse Gas R&D Programme
Pure Offices, Cheltenham Office Park,
Hatherley Lane, Cheltenham
Gloucestershire
GL51 6SH
United Kingdom

Or by telephoning the office on:

+44 (0)1242 802911

Disclaimer

The GHG TCP, also known as the IEAGHG, is organised under the auspices of the International Energy Agency (IEA) but is functionally and legally autonomous. Views, findings and publications of the IEAGHG do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

Date Published: May 2022
Review compiled by Tom Billcliff, Suzanne Killick, Tim Dixon and James Craig.
Document designed by Tom Billcliff.

Inside Cover Image: National Carbon Capture Center, Wilsonville, Alabama, USA. Image courtesy of Southern Company.
Front and Back Cover Images: Speakers at the CCS side event at COP26, CCS in the Emerging Economies of Nigeria, Trinidad and Tobago, Indonesia, and India; Abu Dhabi at night, host city for GHGT-15; Students & Lecturers at the ITB-IEAGHG Virtual CCUS Course, August 2021; Technology Centre Mongstad, Norway.

Annual Review Contents

Tomakomai CCS Demonstration Center at night. Image courtesy of Japan CCS Co., Ltd.

Chairman's Message

As the world recovered from the economic hit of COVID restrictions, it was disappointing to see CO_2 emissions rise again, and the atmospheric levels reached 419 ppm by the end of the year. Arctic sea ice was at its lowest recorded level, and other climate impacts continued to worsen.

The IPCC released the first of their three reports from AR6. Their update on the science of climate change is lucid and concerning. It includes new evidence from climate science, and re-emphasises why we need to reduce emissions quickly, and why CCS is needed for permanent CO_2 removal (CDR). It is very comprehensive in its 3949 pages, covering the current state of the climate, the future climate, risk and adaptation, and limiting future climate change. It explores why and how CDR is needed to compensate for residual emissions in-order to reach net-zero. A sobering conclusion is that even with achieving sustained net-zero emissions, while there would be limits to temperature increases and gradual reversals of atmospheric CO_2 and surface ocean acidification, climate change already in the global system would continue for decades and more.

Another significant report in 2021 was from our colleagues in the International Energy Agency, "Net Zero by 2050 – A Roadmap for the Global Energy Sector". This had some headline-grabbing aspects on no new fossil fuel supply projects, and re-emphasised the need for CCS in order to achieve net-zero by 2050, with some 4 Gt CO_2 pa being captured by 2035 and 7.6 Gt pa by 2050.

COP-26 finally took place, hosted by the UK in Glasgow. This stimulated new pledges from countries, resulting in emission trajectories coming downwards, but not enough, although moving in the right direction. I am pleased that IEAGHG played an active role in sharing information on CCS to delegates from around the world.

Kelly Thambimuthu at GHGT-14, Melbourne

We achieved a first this year, in holding our flagship GHGT-15 conference in a full virtual mode, and managing to include the usual number of up-to-date presentations, keynotes and discussion panels. Another milestone for IEAGHG was our 30th anniversary this year, and we will be producing a special report to highlight all the achievements and developments in CCS from the start of our pioneering activities in 1991.

We look forward to seeing our international colleagues more in-person in 2022, in continuing our work with a renewed pioneering spirit and unabated urgency, whilst keeping safe and well.

K.V. Thambimuthu.

Kelly Thambimuthu,
Chairman of the IEAGHG Executive Committee

General Manager's Summary

I am very pleased to say that IEAGHG continued to work well under the COVID restrictions which varied throughout the year, mostly working remotely and our output remained high.

Which is important because CO_2 emissions rose back to pre-pandemic levels, climate change continued, and CCS developments continued around the world.

Most significantly for us was delivering GHGT-15 in a fully virtual format, with our hosts Khalifa University in UAE. We managed to take the already-selected full technical programme and deliver it virtually, with over 500 presentations in seven parallel sessions over four days. This was a first for the CCS world, and whilst it involved a steep learning curve, afterwards we shared our learnings with others planning to also host virtual CCS conferences.

We continued with our international expert networks meeting virtually, and we again provided a summer school in virtual format with our hosts ITB in Indonesia.

Of even more significance was that the postponed COP26 took place, in Glasgow. This was intended as the first update of the Nationally Determined Contributions (NDCs), and with the rush of updated and revised NDCs just before COP this took our emissions trajectory from 2.7C to 2.4C (warming at the end of this century). Not enough but moving in the right direction. The IEA's analysis which looked at the net zero pledges saw a similar improvement from 2.1C to 1.8C.

Tim Dixon, IEAGHG General Manager

As well as updated NDCs, the Paris Agreement calls for countries to submit long-term greenhouse gas strategies looking to mid-century, and most of these have CCS included. So we have a lot of work to do to help these countries realise their CCS potential. For IEAGHG it was also a successful COP, organising two side-events (one official UNFCCC) with our partners, and speaking at several others. As the first such major event that was in-person, it was a success in terms of low-COVID rates and also a success for achieving more at the COP, certainly we were very busy!

Tim Dixon,
IEAGHG General Manager

A growing theme at this COP was CO_2 direct removal (CDR), with the IPCC's climate science report featuring CDR significantly (and citing IEAGHG work) and many more side events discussing various aspects of these suite of techniques and technologies. Our recent work on techno-economic analysis of negative emission technologies, on direct air capture costs and constraints, and on carbon accounting of CDR is very relevant and needed.

As we end the year, we have already started working with our French hosts in organising GHGT-16, to be held in Lyon, France, in October and in-person. We very much look forward to seeing many of you there and at the associated meetings which always get arranged around the largest international gathering on CCS.

Key IEAGHG Achievements in 2021

Meetings

PCCC-6 Conference
Over 200 attendees

IEAGHG Monitoring Network – Webinar & Virtual Discussion: Monitoring Expertise Showcase for Post-Closure Monitoring
63 attendees

2021 ITB-IEAGHG Virtual CCUS Course
Over 250 attendees

IEAGHG-IPA Pre-Convention Short Course on CCUS for Executives
45 attendees

External Presentations by IEAGHG Staff

Published to Online Media

4 Webinars
1,768 YouTube views

5 Technical Reports
5 Technical Reviews
29 Information Papers

Page Views: 113,200
Views of IEAGHG Website: 60,440 Sessions

IEAGHG Operations Report

Membership continued with 35 members. We welcomed BP rejoining, and we are progressing other new members and responding to enquiries from other organisations as global interest in CCS development and deployment continues to grow.

Our total annual income was approximately £1.5m, and the budget was allocated as illustrated below.

The Executive Committee, which is comprised of our member representatives and acts as the governing body overseeing IEAGHG's activities, met twice in the year. Because of COVID both meetings were held virtually. Despite time restrictions due to spanning the 19 time zones of members, they managed to cover full agendas in terms of directing the technical programme, governance and reporting purposes.

Note 1: This spans over two financial years so values given here are approximated. Audited ccounts are available to members.
Note 2: COVID reduced some of the final expenditure on travel and meetings.

Drone photo of Project E CO_2S field operations and the drilling of one of the six test wells. Photo: R.A. Esposito

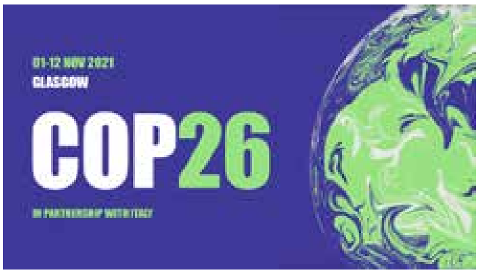
Facilitating Implementation

IEAGHG helps to facilitate the implementation and deployment of CCS by contributing the technical evidence-base to policy-makers, regulators and other decision-makers.

IEAGHG participates in key activities to support CCS policy/implementation strategies and by undertaking studies and workshops to provide information that is needed to assist development and deployment. 2021 was another challenging year because COVID meant that many of the usual meetings continued to be fully virtual or postponed to 2022.

UNFCCC COP26

Given the immense challenges of climate change, all COPs are important, but COP26 was going to be a particularly important COP in that it was the time for the updates of each country's Nationally Determined Contributions (NDCs) and aiming to finalise the rules to implement the Paris Agreement. The UK presidency of COP wanted to achieve these and to keep limiting warming to 1.5C within reach. The end result did achieve these objectives.



Glasgow Climate Pact

In the late hours of Saturday the 13th November the 197 countries at COP26 agreed on a new agreement to build upon the Paris Agreement, called the Glasgow Climate Pact.

From our mitigation perspective, the most significant aspects of this Glasgow Climate Pact include that the Nationally Determined Contributions (NDCs), which were required to be updated every five years (ie 2020, 2025, 2030) will now have to updated again by the end of 2022 (still with the target year of 2030). Also significant is that fossil fuels are explicitly mentioned for the first time in such an agreement. As the draft text developed over the days, we were pleased to see the clarification of "unabated" being added to the phasing-down of coal, meaning that coal use needs to have CCS to continue.

The Glasgow Climate Pact includes clear recognition of the importance of scaling up deployment of clean energy technologies. The importance of the science base for policy-making was also emphasised in the Glasgow Climate Pact, "welcoming" the IPCC's Working Group I report on the science of climate change (see IEAGHG Information Paper 2021-IP14). IEAGHG will continue to monitor and input to IPCC's Working Group III work (final report due March 2022).

Article 6

Another major area for this COP was to finalise and agree the unfinished aspects of the 'rulebook' for the Paris Agreement. These primarily relate to Article 6, on international collaboration including through carbon markets. Article 6.2 relates to emissions trading between countries, and Article 6.4 is a project-orientated crediting mechanism (like a new CDM). Both Decisions were finalised, with provisions to ensure their integrity such as 'corresponding adjustments' to ensure no double-counting should take place. These set up structures for carbon markets to work in support of the Paris Agreement, will assist both countries and companies to achieve higher ambitions, and could be beneficial for multinational CCS projects. The hard work of developing and agreeing the CCS CDM modalities and procedures should be beneficial for CCS projects under the new Article 6.4 mechanism. IEAGHG followed the negotiation developments, identifying areas for clarification. Overall from a CCS perspective, it is good that both Decisions are technology neutral and explicitly include removals.

The Article 6 Decisions also call on SBSTA to do further work on some of the details and definitions, including on monitoring and reporting of removals, so work on Article 6 detail is not finished yet, and IEAGHG will continue to track and input to developments.

Climate change

A major objective of the UK Presidency was to keep 1.5C within reach. Certainly, with the rush of NDC updates just before COP, based upon those NDCs, we saw the projection of temperature rise improve from 2.7C to 2.4C. of temperature rise improve from 2.7C to 2.4C.

On a different basis, the IEA's and others' analysis of the new 'net zero pledges' also (which cover some 90% of the world's emissions), there was improvement from 2.1C to 1.8C, with the important caveat that this depends on all pledges and actions are delivered. Many will say that 2.4C is still a long way short of 1.5C, and still depends on the actions in NDCs being delivered. But we have never experienced such progress in temperature projections during a COP, and which are planned to be strengthened further at COP27 with new NDCs.

The UNFCCC Side-event on CCS at COP26: Decarbonising industries in the UK, US, Canada and Nigeria.

IEAGHG at COP26

IEAGHG's role in COP is to be an impartial information provider on CCS and CDR, and we were proud to do this in five side-events (two of which we organised and one being an UNFCCC Side-event) and an exhibit, working with our collaborators the University of Texas, CCSA, Bellona, the International CCS Knowledge Centre, and also with the Global CCS Institute and IPIECA.

We organised two side-events on CCS. The first was on CCS in the Emerging Economies of Nigeria, Trinidad and Tobago, Indonesia, and India. This was organised with the University of Texas and hosted by Bellona. The aim was to share the new developments in these countries and hence encourage "South-South" knowledge transfer. We heard from Dr Victor Richard Osu, Nigeria Office of the Vice President, from Professor Raffie Hosein, University of the West Indies in Trinidad and Tobago, our member Dr Rachmat Sule, Institute Technology Bandung, Indonesia, and Dr Vaibhav Chaturvedi, Council on Energy, Environment and Water, India. Indonesia, Trinidad and Tobago, and Nigeria are all making progress on CCS in their countries. The interest in this event was reflected in that the room was full and with the online audience also we had a total audience of over 300.


Speakers at the CCS side event at COP26, CCS in the Emerging Economies of Nigeria, Trinidad and Tobago, Indonesia, and India

The second event was the official UNFCCC Side-event on CCS Decarbonising industries in the UK, US, Canada and Nigeria. This was organised by ourselves with the University of Texas, CCSA, the International CCS Knowledge Centre and Bellona. We heard from Dr Jennifer Wilcox, Principal Deputy Assistance Secretary, US DOE, Ruth Herbert, CCSA, Dr Katherine Romanak, University of Texas, Dr Victor Richard Osu, Nigeria Office of the Vice President, Eivind Berstad, Bellona, and Beth Valiaho and Niall McDowell, International CCS Knowledge Centre. The attendance to this studio-based event was over 200 people online, again showing the continuing interest in CCS at COPs. The event got good coverage from the COP media service from IISD, providing a nice summary, see Highlights and images of main proceedings for 11 November 2021 (iisd.org)

IEAGHG also presented at other side-events organised by the Global CCS Institute and IPIECA, contributed to a virtual exhibit with our partners, and reported to members on developments during COP with five blogs.

For the recordings of the two side-events, a listing of other CCS-related side-events, and blogs from during COP26, see CCUS-related events at COP26 (ieaghg.org) . For more detailed information on the agreements and outcomes of COP26, we recommend IISD's detailed summary Glasgow Climate Change Conference | IISD Earth Negotiations Bulletin.

IPCC

IEAGHG are accredited as Observers to the IPCC, so that we can improve our opportunities for input. The IPCC is currently in its Sixth Assessment cycle. IEAGHG focusses most of our input to IPCC's Working Group III (Mitigation). In 2021 IEAGHG provided 67 Expert Review comments to the Second Order Draft (FOD). Most IEAGHG comments were given to Chapter 6 Energy Systems. Whereas this chapter in the FOD was reasonable on CCS, new material had been included on CCS here and some was in our view biased, selective or wrongly negative, for example on water usage with CCS and DACCS, on CCS technology maturity and risk, and BECCS potential. We were able to draw upon recent IEAGHG reports and related papers to counter or balance these aspects.

Also during 2021, the IPCC finalized the first part of the Sixth Assessment Report (AR6), 'Climate Change 2021: The Physical Science Basis', the Working Group I (WGI) contribution to AR6. This report from IPCC's WGI is their update on the science of climate change. It includes new evidence from climate science, and re-emphasises why we need to reduce emissions quickly, and why CCS is needed for permanent CO_2 removal (CDR). It explores why and how CDR is needed to compensate for residual emissions in order to reach net-zero. Whilst IEAGHG's main input is to IPCC's WGIII (Mitigation) it was noted that IEAGHG work was also cited in this WGI report, an IEAGHG, IEA and IMO co-authored paper from GHGT-12 in 2014 on the London Protocol.

London Protocol

The London Convention and the London Protocol are the global marine treaties that protect the marine environment. We previously reported on the CCS amendments and the 2019 Resolution to allow export of CO_2. In 2021 to provide easier access to and understanding of the London Protocol's detailed guidance and guidelines for export of CO_2 for offshore storage, IEAGHG produced a report, IEAGHG 2021-TR02.

For the annual meeting of the Parties in 2021, LC43, IEAGHG was the only CCS-related organisation attending.

For the CCS agenda item in terms of the 2009 amendment, there was no further progress in the acceptance of the CO_2 export amendment 2009, still just seven countries. This is why the Export Resolution on Provisional Application in 2019 was needed to allow export of CO_2 for offshore geological storage ahead of the coming into force of the 2009 amendment.

Under the CCS agenda item, which calls for updates on relevant activities, IEAGHG reported by submitting an information paper on updates on offshore CO_2 sequestration (as CCS is known in the LC) and by a verbal summary in plenary.

Given the number of offshore storage projects proceeding, there was a request for Parties to report as much detail as possible on their permitting, including how the London Protocol guidelines and guidance are used.

Under the Marine Geoengineering agenda item, the status of the 2013 amendment to regulate marine geoengineering is that it has been accepted by only six Parties, far short of the two thirds needed of the 53 Parties to the London Protocol for it to come into force. Also reported was some work from the London Convention Scientific Group's meeting. Most notably, a proposal to add more techniques to 2013 amendment to regulate marine geoengineering, which allows listed techniques but for research purposes only. The only current technique covered is ocean fertilisation. Proposed to be covered in future work are: fertilization for fish stock enhancement; macroalgae cultivation for sequestration including artificial upwelling; reflective particles/material; adding alkaline material directly to the ocean; coastal spreading of olivine; and mineralization in rocks under the seabed. In this LC43, this proposal was supported by a request for urgent consideration of [note the new term] "ocean interventions for climate change mitigation" beyond just ocean fertilization, given the growing interest in such techniques and the coverage in the recent IPCC WG1 report. So we can expect to see more consideration of these geoengineering techniques in future Scientific Group meetings.

CSLF

The Carbon Sequestration Leadership Forum (CSLF) is a government-to-government agreement on developing CCS, it started in 2003 and now has 25 member countries and the European Commission. IEAGHG and the CSLF Technical Group have an agreed 'Collaborative Arrangement' since 2007, and IEAGHG has produced nine reports from three studies and six workshops for the CSLF.

Both of the CSLF Technical Group's meetings in 2021 were held in virtual format, and IEAGHG attended to present updates on IEAGHG activities, support the strategic planning, participate in the active task forces, and to support the updating of the CSLF Technology Roadmap which was published in 2021 (See IEAGHG Information Paper 2021-IP16 for a summary).

carbon sequestration leadership forum

ISO TC/265

ISO

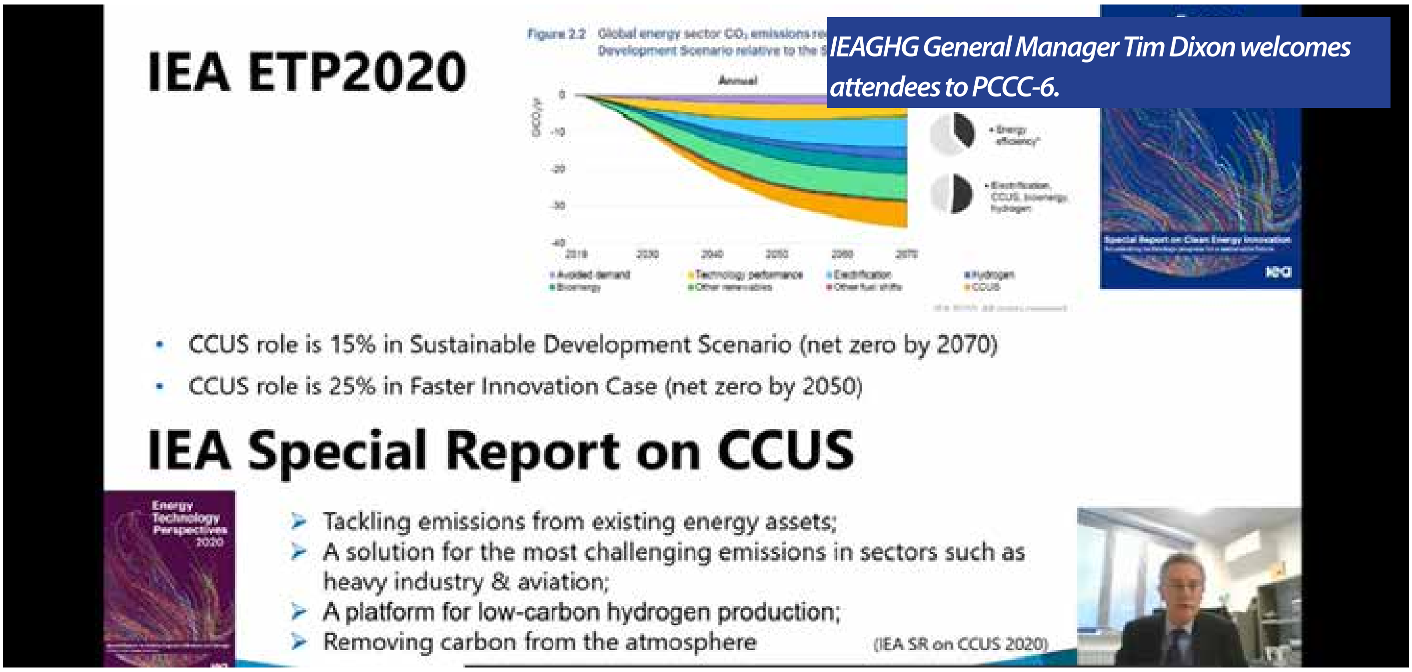
This ISO committee was proposed by Canada and set up in 2012 with a Canadian Chair and Canadian and Chinese Secretariat.

There are 19 participating countries, 13 observing members, and 7 Liaison organisations. It consists of six working groups: WG 1 Capture; WG 2 Transport; WG 3 Storage; WG 4 Quantification and Verification; WG 5 Cross-cutting issues; WG 6 CO_2 -EOR. IEAGHG is a Liaison Organisation to TC265, and is a member of WG 3 and WG5. So far, TC265 has published 5 standards and 5 technical reports.

The last plenary was held virtually on the 23rd June 2021. IEAGHG provided an update to input our technical reports.

IEAGHG 6th Post Combustion Capture Conference – PCCC-6

Together with our host organisation, the UK Carbon Capture and Storage Research Council (UKCCSRC), IEAGHG delivered a very successful sixth conference in this series.



IEAGHG General Manager Tim Dixon welcomes attendees to PCCC-6.

Given the recognition it has achieved, the conference series has become a magnet for the presentation of high calibre papers and posters and, consequently, for all those wishing for an update on the global status of post combustion capture. As with its predecessor IEAGHG conference, GHGT-15, PCCC-6 was delivered wholly online as a virtual event – a first for both. The three-day conference was held from 19 to 21 October and attracted more than 200 attendees from 22 countries. As if to illustrate the broad geographical interest in the subject matter, the only continent not represented at PCCC-6 was Antarctica.

PCCC-6 was opened with welcome addresses from two distinguished and long-serving figures in the CCUS community, IEAGHG's Tim Dixon and UKCCSRC's Jon Gibbins. An excellent line-up of keynote speakers began day's two and three, providing context for the information shared during the technical presentations. Ruth Herbert (CCSA) discussed the UK government's policy on CCUS and potential business models to take the technology forward. Her reflections on the economic benefit of several proposed CCUS clusters in the UK shortly preceded a major UK government announcement where two clusters were selected to proceed to the next stage. Bryony Livesey (UKRI) built on Ruth's presentation with insights into UKRI's ambitious plans for joint government/industry funding designed to deploy CCUS and enabling infrastructure in heavily industrialised regions of the UK.

Takashi Kamijo described MHI Engineering's long experience of developing and deploying CO_2 capture technology, including its role in providing the capture technology for the Petra Nova project, the World's largest capture facility to date, capturing almost 500 tonnes of CO_2 per day. US DOE's Lynn Brickett described the mission of the Biden Administration to achieve a net-zero US economy by 2050, its chief focus areas, budgets and principally its very impressive CCUS and hydrogen programmes.

GCCSI's new Chief Executive, Jarad Daniels, provided delegates with insight into progress on CCUS internationally, the roles the CEM CCUS initiative, the CSLF and the IEA in promoting policy and deployment, and on GCCSI's role accelerating the deployment of CCUS globally. The final keynote was given by Conway Nelson of Canada's International CCS Knowledge Centre, who provided some excellent insights into lessons learned from Boundary Dam, the world's first large-scale CCUS project in the power sector, and into the Centre's plans for advancing carbon capture technology for second-generation and industrial application.

The centrepiece of PCCC-6 was, of course, its technical programme. Having established itself as the world's leading conference series addressing post combustion CO_2 capture, PCCC-6 provided the perfect forum to discuss up-to-the-minute topics relating to the status and development of the technology, and to foster prospects for collaborative study. Seventy excellent technical presentations across seven sets of parallel sessions underpinned the conference, presentations selected by the PCCC-6 Steering Committee from the wealth of abstracts submitted. Delegates shared and discussed their experiences and knowledge on all aspects of the technology, from innovative research to demonstration and beyond, from new and improved solvents to novel separation technologies, from technology cost to environmental impact. Technical highlights were many and, while IEAGHG does not publish a conference proceedings, a broad appreciation of the technical content is available in the 6th Post Combustion Capture Conference Summary.

With more than one hundred CCUS facilities at different stages of development across the world, post-combustion capture is sufficiently technologically mature to decarbonise a broad spectrum of those assets. It was clear that post-combustion capture would have an essential role to play in many of the countries that had pledged to achieve net-zero economies via decarbonisation of its assets. Technology, economics and the environment will be central to this endeavour, all areas where delegates to PCCC-6 have been and will increasingly play their part.

In a nutshell, virtual PCCC-6 was a resounding success. Apart from the sterling effort put in by our hosts, credit for this goes to all the delegates, presenters, chairs and sponsors that contributed to its delivery. We particularly thank all the delegates that logged into sessions and stayed online to take part in the Q&A – acknowledging that, for many, unsociable hours were the norm! Special thanks also go to our sponsors – the International CCS Knowledge Centre, MHI Engineering, the US National Carbon Capture Centre, Petrofac, the US Department of Energy and UK Research and Innovation. As the PCC Conference series is organised on a not-for-profit basis, sponsorship is key for us to break even while keeping registration fees at the lowest possible level.

IEAGHG now begins the search for a host and location for PCCC-7. By September/October 2023, we very much hope to be in a post-COVID world that allows us to meet each other in person once again.

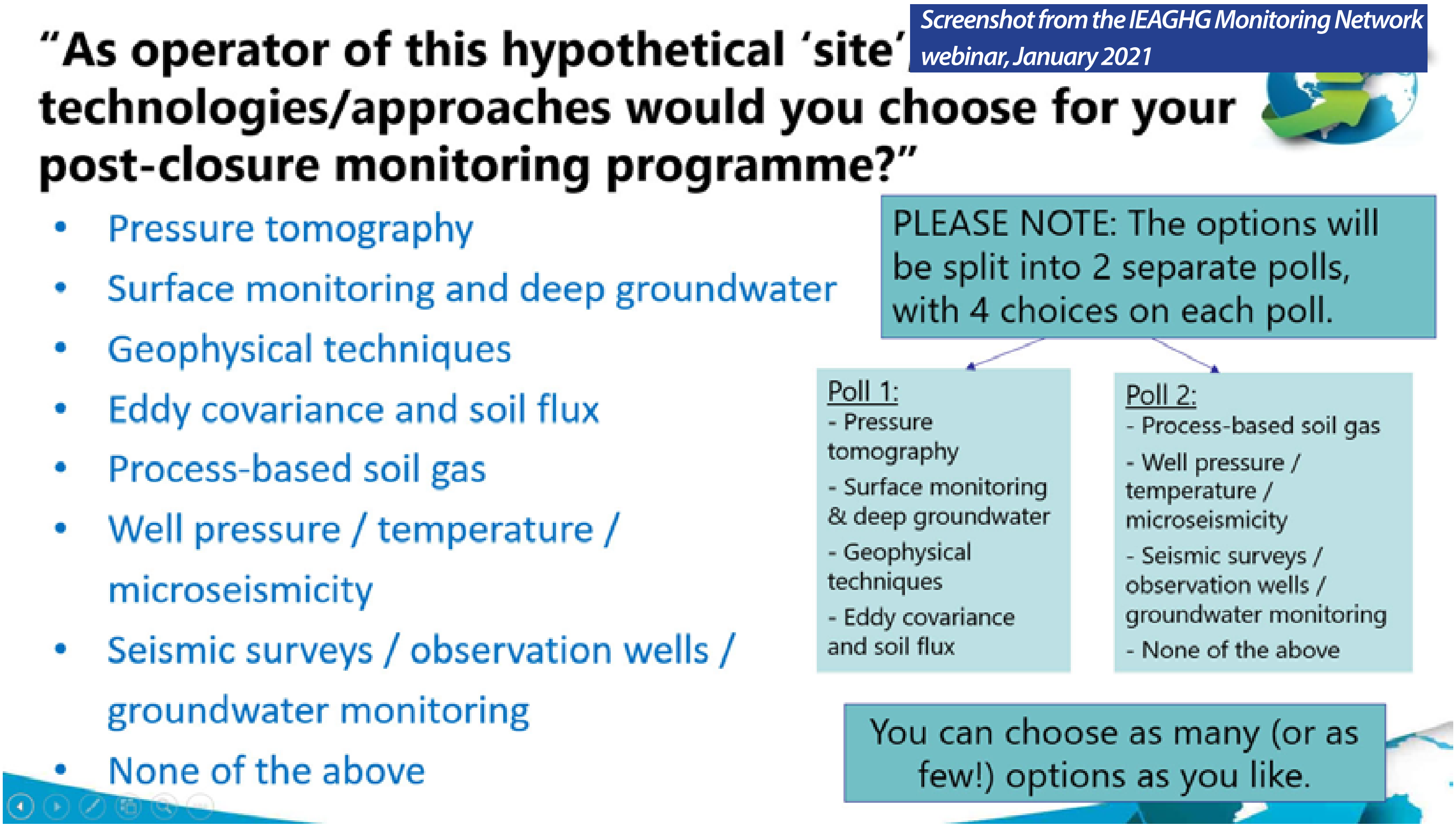
Evaluating technology options to mitigate greenhouse gas emissions

pccc-6

Post Combustion Capture Conference

IEAGHG Monitoring Network – Webinar & Virtual Discussion: Monitoring Expertise Showcase for Post-Closure Monitoring

On the 26th January 2021, a virtual event was held for the IEAGHG Monitoring Network, an expertise showcase for post-closure monitoring. 63 attendees joined the webinar, in addition to 19 panellists and 2 IEAGHG support staff.



Screenshot from the IEAGHG Monitoring Network webinar, January 2021

This was a little different from usual webinars, whereby the Steering Committee aimed for a more interactive and informal experience for the audience with a scenario-based exercise. Experts in the area of post-closure monitoring were invited prior to the webinar to propose how they would approach a post-closure monitoring plan for a given hypothetical CO_2 storage site.

These hypothetical proposals were presented to the webinar audience (who were acting as the site developer) and following questions and discussion from the IEAGHG Monitoring Network Steering Committee, the audience was invited to vote on which technologies they would choose as a developer for this hypothetical site.

The panellists discussed a series of topics throughout the event, provoking thoughtful and interesting discussion: Many topics were looked into around the area of post-closure monitoring for CO_2 storage sites, and several key messages were drawn from the discussion:

- There is a wide range of available technologies that can be deployed for post-closure monitoring programmes, all of which have different merits,
- Post-closure monitoring is very site specific,
- Effective and proper post-closure monitoring requires a full and detailed site characterisation, baseline knowledge and a lot of data from the area before a site can be approved,
- It's important to do both operational and post-closure monitoring,
- Leakage is defined as CO_2 that fluxes across the ground surface and not out of the reservoir; greenhouse gas emissions accounting is concerned with the CO_2 reaching the air or water column,
- More work is needed on deep monitoring methods informing the near surface methods in real time,
- The subsurface is known well but operators need to be prepared for any changes,
- It is likely and recommended that monitoring programmes will use a variety of technologies that complement one another,
- Shallow and surface monitoring may be needed as assurance monitoring,
- Responding to stakeholder concerns is an important facet of monitoring programmes,
- Environmental liability differs in different regions,
- False positives are an important factor to consider when choosing technologies,
- Understanding of post-closure monitoring approaches is still immature,
- Geological CO_2 storage is safe by design, and is designed to be safe.

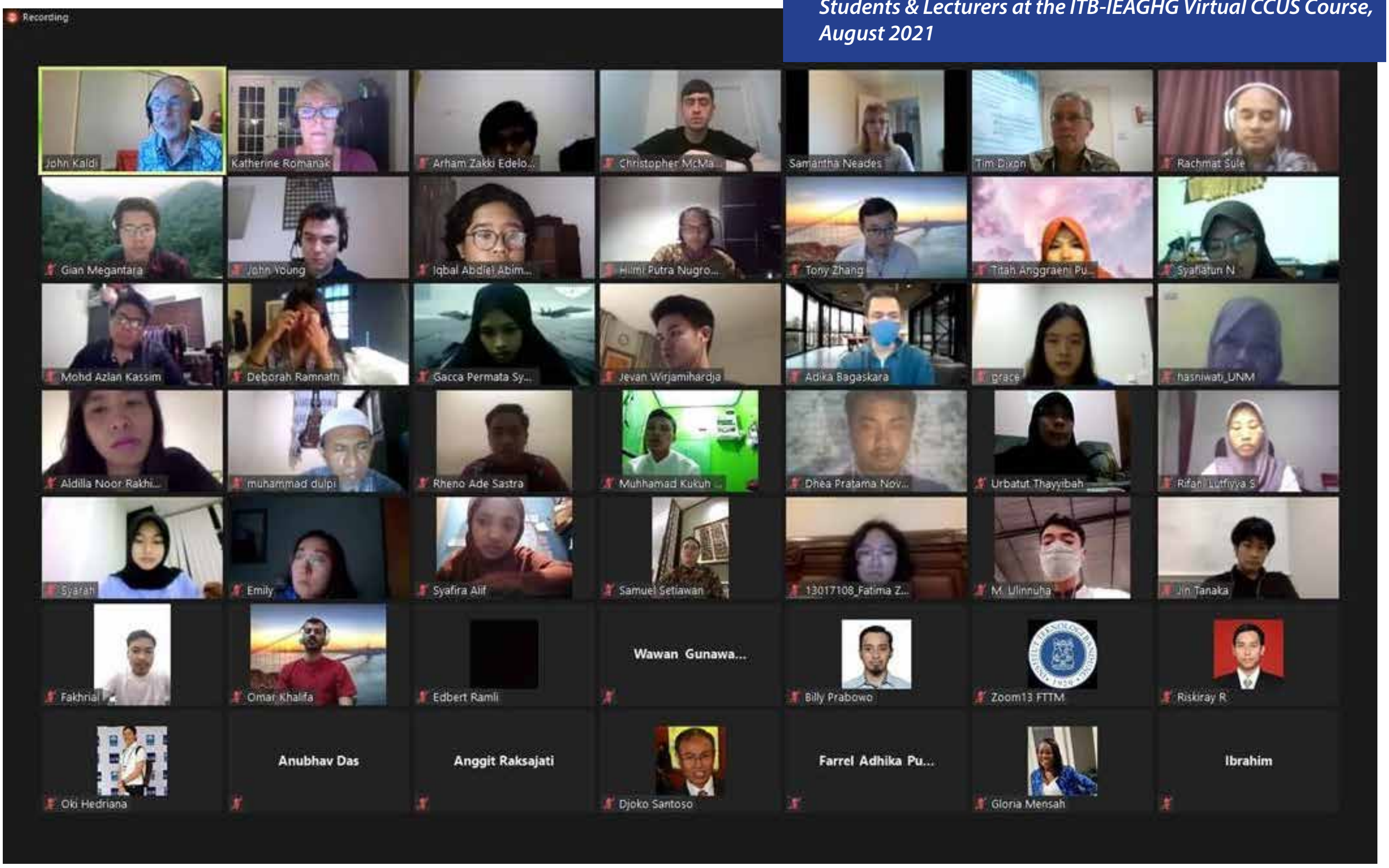
A full review of the webinar was produced by IEAGHG to summarise the discussions and draw out main conclusions. This can be requested from IEAGHG, quoting report number 2021-TR03.

2021 ITB-IEAGHG Virtual CCUS Course

In 2021, IEAGHG continued its collaboration with Institut Teknologi Bandung (ITB) on their efforts to facilitate knowledge sharing with the second Virtual CCUS Course, held from the 26th July to the 6th August 2021.

The 2020 IEAGHG International CCS Summer School was due to be hosted by ITB, in Indonesia, but was postponed due to COVID-19 so in the interim before the next in-person event, two virtual courses on CCUS were held in November 2020 and July / August 2021. This most recent event accepted over 250 attendees (three times more than the 2020 course!) who included both current students in education and professionals looking to further their knowledge in the area from all over the world.

Students & Lecturers at the ITB-IEAGHG Virtual CCUS Course, August 2021



Throughout the two-week course, over 40 lectures were given on all aspects of CCUS, including in-depth lessons on capture, transport, storage, legal and regulatory, environmental impacts, direct air capture, BECCS and public communication. Experts from ITB, IEAGHG, the University of Adelaide, CO2CRC, Pertamina University, National University of Singapore, MIT, the International CCS Knowledge Centre, IIASA, RITE, Total Energies, ExxonMobil, Shell, Janus, Gassnova, BEG at the University of Texas, University of Pennsylvania, IITB Mumbai, Fukada Geological Institute, Monea CCS Services and the Global CCS Institute volunteered their time to provide these invaluable lectures to attendees. IEAGHG would like to thank the hosts of the virtual course, ITB for their hard work in facilitating and organising the event, and of course the valued speakers.

IEAGHG and ITB are hopeful that in-person IEAGHG Summer School will be able to go ahead in early August 2022. Students have already been accepted to this School, but if you are a current student or early career professional who may be interested in attending a future IEAGHG International Summer School, please visit the website at https://ieaghg.org/summer-school or sign up to our mailing list for updates on the programme.

IEAGHG-IPA Pre-Convention Short Course on CCUS for Executives

IEAGHG were invited by ITB to run a short course on CCUS for high-level executives and government representatives from Indonesia on the 19th August 2021.

IEAGHG were invited by ITB to run a short course on CCUS for high-level executives and government representatives from Indonesia on the 19th August 2021. This short course was held as a pre-convention event for the Indonesian Petroleum Association (IPA), prior to its 45th annual convention and exhibition which took place from the 1st to 3rd September 2021. The aim of this 3.5-hour event was to give an insight into CCUS and provide attendees with valuable lessons to help them make decisions at and following the main convention. This event was led and moderated by IEAGHG, with experts from the IEAGHG CCS Summer School lecturer pool contributing to the technical content.

The topics covered during this short course included a welcome to the IEAGHG programme, a brief overview of the CCUS value chain; technical learnings for the storage of CO_2; monitoring and verification of CO_2; CCUS activities in Indonesia; international policy, legal and regulatory frameworks; and upstream-linked CCUS activities in the Asia Pacific region.

It was a fantastic opportunity for IEAGHG to be invited by the IPA to run this course and the event was extremely well received by all 45 attendees. IEAGHG would like to thank IPA for the invite and express our gratitude to our speakers who contributed to the event: John Kaldi (CO2CRC), Katherine Romanak (BEG at the University of Texas at Austin), Rachmat Sule (ITB), Antonio Dimabuyu (IHS Markit), and Tim Dixon (IEAGHG).

2021-01 Biorefineries with CCS,

report managed by Jasmin Kemper

Negative emissions technologies (NETs) feature in many climate models that comply with 2°C scenarios; and efforts to aim towards a 1.5°C target, as outlined in the Paris Agreement, have drawn further attention to the need for options that reduce the overall stock of emissions in the atmosphere. Negative emissions are also an important tool for offsetting residual emissions from the hard-to-abate sectors like aviation, cement and steel industry, as well as agriculture to achieve overall carbon-neutrality.

A range of plausible NETs have been proposed, and some of them are currently more developed than others, in terms of both technological maturity and the amount of CO_2 removal that could potentially be offered. As NETs are growing in prominence in energy planning, better understanding is needed of the many trade-offs that achieving negative emissions have on cost, emissions and the required resources. The longer-term growth of transport biofuels in the IEA's 2DS relies on the widespread supply of novel advanced biofuels produced by processes that are generally not yet mature. Advanced biofuels are sustainable fuels produced from non-food crop feedstocks that are capable of delivering significant life-cycle GHG emissions savings without competing with food and feed crops for agricultural land use. Advanced biofuels can also be called "second generation" (2G) biofuels, to differentiate them from "first generation" (1G) crop-based biofuels. The sustainable conversion of biomass feedstocks to biomass-derived fuels and chemicals are often referred to as "biorefining". In addition to biofuel, such "biorefineries" typically produce also by-products and CO_2. The CO_2 from biomass processing is normally vented to atmosphere, but if it were captured and securely sequestered in geological formations (BECCS), the produced biofuel could be characterised by net negative GHG emissions because of the storage of biogenic CO_2.

The aim of this study is to provide a techno-economic assessment of biorefinery concepts with and without CCS as well as a comparative assessment of 1G and 2G biorefineries. The results of this study will be of interest to developers of biorefinery and CCS projects and policy makers.

Key Messages

- The cost of adding CCS on the high-concentration streams of biorefineries varies between 22 and 24 $/t$CO_2$. If CCS is extended also to flue gas streams, the cost of CCS varies between 27 and 66 $/t$CO_2$. The wider range of cost is explained by differences between biorefineries in the share of CO_2 that needs to be captured from low-concentration streams.
- The lowest cost of CCS is achieved with gasification-based configurations using base case CCS design (22 $/t$CO_2$) followed closely by ethanol plants with base case CCS design (24-25 $/t$CO_2$).
- Several of the cost estimates are developed for first-of-a-kind (FOAK) commercial plants and contain a lot of uncertainty as they are derived from a small handful of demonstration projects. Cost reductions could be achieved over the coming decades through learning from these technologies at relevant for decarbonising the hard-to-abate transport sector. On the other hand, the cost scale.
- Biorefineries with CCS show potential for negative emissions. First generation corn ethanol plants with CCS can only produce carbon negative fuels if natural gas inputs are switched to a low-carbon energy source. For second generation biorefineries with CCS, based on woody biomass, emissions range between -59 gCO_2eq/MJ and -164 gCO_2eq/MJ. The deepest emissions reductions in comparison to the fossil reference are associated with second generation wheat straw plants with CCS, which can achieve -274 gCO_2eq/MJ in the maximum capture configuration.
- Biorefineries with CCS seem very attractive, especially as biofuel is currently too high to compete with petroleum fuels and, out of the examined configurations, only two have currently been demonstrated at commercial scale.
- Recommendations for further work include:
  - Implementation of large-scale demonstration projects in order to reduce risk and increase investor confidence.
  - More data should be made available from projects in order to refine the techno-economic assessment of biorefineries with CCS and reduce uncertainties.

2021-02 CO_2 as a Feedstock: Comparison of CCU Pathways

report managed by Jasmin Kemper

A range of carbon dioxide capture technologies have been developed, including amine-based routes and calcium looping methods, some of which are now considered to be at technology readiness level (TRL) 9.

These technologies have been deployed across the world in large-scale carbon capture, utilisation and storage (CCUS) projects, permanently storing the CO_2 in geological formations, which in 2020 had a capture and storage capacity of 40 $MtCO_2$ per year. Direct air capture (DAC) technologies, capable of capturing CO_2 directly from the atmosphere, have recently been developed and demonstrated.

As well as storing the CO_2 in geological formations, there is increasing interest in the chemical transformation of captured CO_2 to value-added products, such as building materials, chemicals, polymers, and synthetic fuels. This is driven partly by goals to increase sustainability, lower emissions, and the move towards more circular production routes. Developments have also been driven by realisations that producing some products using CO_2 as a feedstock could lead to improvements in the product or the process, such as enhanced properties or lower feedstock costs. CO_2 is already used extensively for urea manufacture in the fertiliser industry, for enhanced oil recovery (EOR), and for food and beverage production, with other conventional applications including use in fire-extinguishers, greenhouses, and cooling systems. Carbon capture and utilisation (CCU) refers to CO_2 utilisation in which the supplied CO_2 is captured either from an emission point source (e.g. fossil fuel combustion in an industrial plant) or directly from the atmosphere (DAC). With large volumes of CO_2 projected to be captured in the longer term, CCU and CCS can play complementary roles in climate change mitigation.

For many utilisation routes, CO_2 sequestration is only temporary with utilised CO_2 being emitted to the atmosphere as the product is combusted or degrades at its end-of-life. Fuel products may last for less than a year, chemicals less than 10 years, and polymers less than 100 years. At the end of the product's life, the carbon atoms contained within these products often enter the atmosphere as CO_2, with exceptions where this carbon is captured and stored permanently, e.g. in building materials. In absolute terms, these re-emitting CCU routes are therefore carbon neutral at best but typically net-positive in emissions when their entire life cycle is considered.

Key Messages

- Almost all CCU routes showed potential for lower life cycle emissions per tonne of product compared to their counterfactual. The potential scale for deployment was much greater for fuels and building materials than for chemicals and polymers, which typically had existing markets orders of magnitude smaller.
- For fuels, annual abatement levels greater than 1 Gt CO_2-eq could be achieved for direct replacement 'drop-in' fuels. For building materials, annual abatement levels greater than 100 Mt CO_2-eq could be achieved. CCU building materials also have potential to offer negative emissions when CO_2 is sourced from DAC. With the exception of methanol, the total mitigation potential of polymers and chemicals was limited to below 20 Mt CO_2-eq per year.
- Most CCU routes within the chemicals and fuels categories were found to be considerably more expensive than conventional fossil-based production routes, due to high energy requirements for green hydrogen feedstock, low yields and high catalyst costs. CCU building materials and polymers can offer cost reductions.
- There are a range of potential co-benefits (e.g. re-use of waste residues, raw materials reduction, safer production process, improved product properties, energy storage) for CCU routes but there can also be trade-offs (e.g. high energy demand, additional land-use, increased water consumption).

- Deployment of CCU routes may be more favourable in regions with: (i) low-cost or extensive availability of renewable energy; (ii) high cost or lack of available fossil resources; or (iii) significant low-carbon ambition coupled with political or regulatory mechanisms. The current distribution of CCU R&D projects is concentrated mostly in the EU and the US.
- CO_2 utilisation opportunities are diverse, and each route has its own specific drivers, barriers, and enablers. There are, however, some common themes that span across, e.g.: regulations such as mandates or standards, financial provisions, policies that level the field by recognising sustainability benefits, sustainable product development, regional energy availability, costs.
- Recommendations:
  - Report sufficient data to allow for life cycle and techno-economic assessments (LCA and TEA).
  - Highlight priority areas for CCU development and identify end-uses where CCU is expected to be a necessary component of future decarbonisation pathways.
  - Engage with the public and policy makers to improve understanding of the benefits and limitations of CCU routes.
  - Increase awareness of upstream emissions in supply chains and identify opportunities to switch to more sustainable production routes.
  - Introducing support mechanisms that allow CCU to receive recognition for sustainability benefits.
  - Incorporate CCU products appropriately into existing support schemes, regulations, and product standards.
  - Provide funding for research programmes, demonstration projects etc.
  - Develop and clarify frameworks for the carbon accounting of CCU routes.

2021-03 CO_2 Utilisation: Hydrogenation Pathways

report managed by Jasmin Kemper

CO_2 can be transformed into a wide range of value-added products, acting as an alternative carbon source to fossil carbon. These CO_2 'conversion' utilisation routes are of increasing interest due to considerations related to climate change, avoidance of fossil fuels, and the circular economy.

Carbon capture and utilisation (CCU) uses CO_2 captured from industrial emissions or directly from the atmosphere, thus having potential to reduce net CO_2 emissions relative to conventional production routes. CCU can be used to produce chemicals, materials, polymers and fuels that are direct replacements for existing products, conventionally produced from fossil feedstocks. Therefore, CCU can offer a means of producing conventional products whilst avoiding fossil extraction.

The evaluation of CCU routes is often complex, with emissions and costs variable with feedstock assumptions, and 'benefits' dependent upon comparison to a counterfactual. There is currently a lack of information and/or uncertainty around the role that CCU technologies might play in emissions mitigation and the potential scale of CCU deployment. The assessment of these factors requires an understanding of the total emissions associated with CCU products, the costs, and the energy demands. Depending on the product being investigated, estimates of these factors can vary considerably due to a range of potential options for CCU conversion technology, the origins of feedstocks and energy, and geographical factors. In addition, quantification of emissions mitigation requires assumptions around the counterfactual case for comparison, adding complexity. The allocation of costs and emissions across different aspects of the value-chain also adds uncertainty.

The aim of this study is to assess the feasibility of select CCU routes based upon CO_2 conversion through hydrogenation, in terms of their climate change mitigation potential. The commodities selected for investigation were methanol, formic acid, and middle distillate hydrocarbons (synthetic fuels: diesel, gasoline, jet fuel), with a focus on catalytic hydrogenation pathways. Of particular interest is the impact of different feedstock choices (hydrogen, electricity, CO_2 capture) on costs, energy demand and CO_2 emissions.

Key Messages

- Hydrogenation routes require a supply of hydrogen and CO_2, and the origins of these feedstocks impact the overall cost and emissions of CCU pathways. Hydrogen is the most significant cost and emission component for both methanol and middle distillate hydrocarbon CCU production routes.
- Production of commodities via CCU routes is more expensive than fossil routes. All realistic combinations of feedstocks result in higher costs than the counterfactual route under both near- (2020s) and long-term (2050s) assumptions. In the near-term, CCU commodities were found to be at least twice the cost of their fossil counterparts. In the long-term, cost premiums can decrease significantly due to reductions in the cost of green hydrogen and CO_2 capture.
- Economic competitiveness of CCU routes is reliant on a 'cost of emission' being applied. For the optimal pathways considered, cost parity could be achieved in the long-term by implementing a cost of emissions between USD 120-225/tCO_2.
- CCU can offer a lower emission commodity production pathway provided a low-emission electricity source is used for green hydrogen production. Using grid electricity (representative of current European grid mixes) for electrolysis is expected to result in CCU methanol and middle distillate hydrocarbon routes having greater emissions than their fossil counterparts, the same applies to the use of unabated fossil hydrogen production.
- The method of accounting for utilised CO_2 has important consequences. For routes with higher production emissions than their counterfactual, CCU commodities can only claim to have lower emissions than the counterfactual commodities if they are able to account for the utilised CO_2 as offsetting some of their production or end-of-life emissions.
- Avoiding > 1 GtCO_2 requires very high levels of market penetration. CCU methanol and middle distillate hydrocarbons have the potential to abate over 1 GtCO_2 but only if methanol captures the entirety of the current market and then expands into the heavy-duty trucks market plus the plastics markets, and if middle distillate hydrocarbons capture the entirety of today's aviation fuels and heavy-duty trucks market. Formic acid does not have the potential to reach 1 GtCO_2 as even if the CCU product were to penetrate the entire formic acid market, the abatement currently achievable is limited to approximately 2 MtCO_2.
- Energy demands might become a barrier limiting large-scale CCU deployment. Under the investigated 'ambitious CCU' scenario, middle distillate hydrocarbons would require about 26,000 TWh of electricity, almost the entire current electricity production globally.
- CCU pathways must be designed carefully to ensure lower life cycle emissions than the counterfactual. Co-location of assets may reduce costs, particularly in regions with high potential for renewable electricity. CCU could provide an attractive solution in regions with limited CO_2 storage, or with cost or public acceptance challenges for carbon capture and storage (CCS).
- Recommendations:
  - Lab scale research and pilot-demonstrations are necessary to address technical barriers.
  - More life cycle assessment (LCA) and techno-economic assessment (TEA) studies are needed, especially on hydrogen and renewable electricity production.
  - Policies are required to mandate the use of low-carbon products and to increase the cost-competitiveness of CCU products.
  - Streamlining approval processes and standards could help enable timely market entry for new CCU products.
  - Further clarity and global consistency of the accounting of CO_2 in CCU routes is needed.
  - CCU pathways can benefit from advances in CO_2 capture and hydrogen production as well as the sharing of infrastructure with large-scale CCS projects.

2021-04 Assessing the Techno-Economic Performance, Opportunities and Challenges of Mature and Nearly-mature Negative Emissions Technologies (NETs), report managed by Jasmin Kemper

The aim of this study is to provide a transparent framework to evaluate the potential (in terms of sequestered and displaced carbon), and economics (in terms of cost of carbon avoided and removed) of a non-exhaustive selection of NETs pathways. Ecosystem and socio-economic impacts associated with their deployment is also quantified.

The study sets out to help the carbon capture and storage (CCS) community in trying to gain a better understanding of the costs and value of NETs. It also helps the modelling community in being able to better model the role of NETs; and policy/decision makers in having more information on costs, value and scalability of NETs.Waste to energy (WtE) strategies shows the highest economic benefit with optimal GHG mitigation and energy potential. That pathway is recognised as a promising alternative to overcome the waste generation problem, additionally generating renewable energy.

Key Messages

- 11 key performance indicators (KPIs) have been defined and assessed for a select number of NET pathways, including direct air capture (DAC), biochar and bioenergy with CCS (BECCS) for power, fuel, hydrogen, steel and cement production.
- The highest CO_2 removals are achieved in NET pathways that maximize the capture of CO_2, have low energy conversion efficiencies, or have access to low-carbon energy. This is especially important when quantifying the net removal potential of DAC: if the energy is supplied by fossil sources, the amount of negative emissions generated lowers significantly.
- Except for corn-based ethanol, all BECCS to bioenergy pathways achieve net negative emissions in the range of 0.08 - 0.35 tCO_2/GJ. Whilst hydrogen production pathways exhibit high capture rates, the energy conversion efficiency for these processes is also high, so less biogenic emissions are being sequestered in the process compared to other biofuel pathways. The production of biochar via slow pyrolysis leads to a net removal of 0.47-0.89 tCO_2 per tonne of dry mass of feedstock (2.6-3.3 tCO_2 /tchar).
- For pathways involving the production of bioenergy, the amount of CO_2 emissions that can be avoided depends on the carbon intensity and on the products/fuel's substitution factor. In low-carbon power grids, biomass provides a much greater value in decarbonizing the transport sector by substituting gasoline than in the power sector.
- Configurations that maximize the CO_2 capture perform better in terms of certain ecosystem impacts. Due to the lower permanence of carbon in soil compared to geological storage, the production of biochar results in the largest water and land footprints among all routes investigated. These trade-offs might be lower when accounting for the potential long-term agricultural benefits of biochar in soil, which have not been included in the present analysis.
- Recommendations:
    - Demonstration of NETs at scale to improve and validate the existing data.
    - NETs should be included in new and existing emission trading schemes.

2021-05 Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture, report managed by Jasmin Kemper

Direct air carbon capture and storage (DACCS) has some advantages over other negative emissions technologies (NETs). NETs interacting with biomass, such as afforestation, soil carbon storage and bioenergy with carbon capture and storage (BECCS), require significant water and arable land.

Other chemical NETs, such as enhanced weathering, risk changing the chemistry of oceans and rivers. DACCS avoids many of these limitations as it has a comparatively small land footprint, but does require a sustainable energy source, geological CO_2 storage to operate and is relatively immature technology with as-yet unproven deployment potential. Furthermore, the varying levels of modularity of DACCS systems imply potential for easy scaling up and rapid deployment.

Current information on DACCS costs, performance, and impact of plant siting have several data gaps and significant uncertainties. Despite the climate relevance of DACCS technologies, current capture capacities are only at ktCO_2/year levels. Therefore, literature on DACCS is limited to few desk-based models and high-level data shared by technology developers with commercial interests. Consequently, most integrated assessment models (IAMs) either omit DACCS or include it without granularity on specific configurations.

Key Messages

- Although DACCS is more expensive than many carbon mitigation and removal options, careful plant siting and rapid learnings can achieve significantly more competitive DACCS costs.
- First-of-a-kind (FOAK) DACCS projects are likely to range from ~$400-$700/net-tCO_2, when global average solar photovoltaics (PV) costs are used, or ~$350-$550/net-tCO_2, when lowest-cost renewables are used.
- Significant cost reduction can be achieved for nth-of-a-kind (NOAK) DACCS plants, reaching ~$194-$230/net-tCO_2 for 1 MtCO_2/year scale, driven by reduced electricity prices, cost of capital and upfront capital investment. Energy costs can be as much as 50% of long-term liquid DACCS costs. NOAK DACCS costs in the range of ~$150-$200/net-tCO_2 may be achieved if very low-cost solar energy is used. Long-term costs were found to be significantly higher than the industry target of $100/t$CO_2$ captured, except under ambitious cost-performance assumptions and favourable conditions.
- The lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants (if low carbon energy is used).
- Since no large-scale plant is built to date, inherent uncertainties on most parameters are high. The largest uncertainties requiring major assumptions are on capital costs, plant scaling factors, future cost reductions through learning, and solid adsorbent cost-performance dynamic.
- To date DACCS representation in integrated assessment models (IAMs) has been relatively simplistic. Technical parameters compiled and developed throughout this study can be used for representation of DACCS technologies in future IAM studies. IAM practitioners should consider differentiating between DACCS technologies and considering multiple plant configurations. Practitioners should also take care to ensure consistent treatment of financing costs for all technologies across their models. Furthermore, operating and labour costs are likely to be region dependent and IAMs can use reference tables to estimate how these costs could differ between countries.
- Most current DACCS policy support consists of generic R,D&D funding, and financial support aimed at wider negative emissions technologies (NETs) or carbon capture and storage (CCS) technologies. The US, UK, EU, Canada and Australia are key regions with relatively developed CCS regulations and R&D and demonstration programmes targeting carbon removal or general CCS projects. The 45Q tax credits in the US and California's Low Carbon Fuel Standard (LCFS) are currently the only financial mechanisms in the world available for large-scale DACCS projects.

2021-TR01 IEAGHG Risk Management Network: "Risk Management Over Time at Operating and Future CCS Projects" A Webinar & Discussion Panel, report managed by Samantha Neades

In the interim before its next in-person meeting, the IEAGHG Risk Management Network held a webinar aimed primarily at those involved or interested in the risk management of CCS projects.

This webinar heard from the operators at Shell's Quest project about their experiences with risk management at the project, which was followed by a panel discussion between representatives from leading CCS developers, as well as experts in the area of risk management.

This webinar and virtual discussion panel was held on Wednesday 2nd December 2020 at 9pm GMT and attracted an audience of 59, plus 10 panellists and IEAGHG staff. The ninety minute webinar and virtual panel discussion covered a wide range of ideas and conversation points regarding risk management of CCS projects, particularly looking at the evolution of risk during CCS projects' lifecycle. The following conclusions and key messages were drawn from IEAGHG's review of the panellists' discussion:

- The bow-tie risk assessment framework is a trusted approach for containment management of CO_2 storage projects.
- As injection progresses, accumulated experience increases and uncertainties are reduced. Risk management is a process for evaluating uncertainties and developing mitigation plans. This approach reduces exposure to risk as a project evolves.
- The geomechanical integrity testing programme is critical to allow proper understanding of uncertainty in a storage complex.
- As projects increase in size and number, there is also an increase in exposure to risk, but with more data risk assessment can be improved and uncertainties reduced.
- Perceived risk can be equated with adverse events. Perception problems can arise where people do not understand specific technologies or understand the complexity of risk management practices.
- Experience from live projects shows that it is critical that project developers are transparent with their public stakeholders and information is readily available.
- It's important to educate not only the local and wider public, but the regulatory and environmental communities.
- The bow-tie approach is also a powerful communication tool.
- Collaboration and communication between the project and the regulator is an important concept that should be followed by all projects, from planning to implementation, operation and eventual closure.
- Discussion between different regulators is important to share experiences and learning. The Alberta regulators communicate with other regulatory authorities.
- MMV programmes can be adapted and evolve as projects progress.
- Better methods are needed for analysing the significant quantities of data generated from MMV programmes.
- Well integrity management is crucial.

2021-TR02 Exporting CO_2 for Offshore Storage – The London Protocol's Export Amendment and Associated Guidelines and Guidance report managed by Samantha Neades

The London Convention and London Protocol are the global treaties that protect the marine environment from pollution caused by the dumping of wastes. Since 2006, the London Protocol has provided a basis in international environmental law to allow carbon dioxide (CO_2) storage beneath the seabed when it is safe to do so, and to regulate the injection of CO_2 into sub-seabed geological formations for permanent isolation.

However, Article 6 of the London Protocol prohibits the export of waste or other matter for dumping in the marine environment. Therefore in 2019, Contracting Parties to the London Protocol adopted a resolution to allow provisional application of the 2009 amendment to Article 6 of the Protocol to allow export of CO_2 for storage in sub-seabed geological formations in advance of its ratification, which was progressing slowly. This removed the last significant international legal barrier to carbon capture and storage (CCS), and means that CO_2 can be transported across international borders to offshore storage.

This report describes the background, details and requirements of this provisional application of the CCS export amendment, and the details and requirements provided by the two associated guideline and guidance documents, and their implications. This report is intended to assist project operators and regulators in accessing and applying the CO_2 export aspects of the London Protocol.

2021-TR03 IEAGHG Monitoring Network – Webinar & Virtual Discussion: Monitoring Expertise Showcase for Post-Closure Monitoring report managed by Samantha Neades

On the 26th January 2021, a virtual event was held for the IEAGHG Monitoring Network, an expertise showcase for post-closure monitoring. 63 attendees joined the webinar, in addition to 19 panellists and 2 IEAGHG support staff.

This was a little different from usual webinars, whereby the Steering Committee aimed for a more interactive and informal experience for the audience with a scenario-based exercise. Experts in the area of post-closure monitoring were invited prior to the webinar to propose how they would approach a post-closure monitoring plan for a given hypothetical CO_2 storage site.

These hypothetical proposals were presented to the webinar audience (who were acting as the site developer) and following questions and discussion from the IEAGHG Monitoring Network Steering Committee, the audience was invited to vote on which technologies they would choose as a developer for this hypothetical site.

The webinar concluded with a number of key messages drawn from the general discussion:

- There is a wide range of available technologies that can be deployed for post-closure monitoring programmes, all of which have different merits,
- Post-closure monitoring is very site specific,
- Effective and proper post-closure monitoring requires a full and detailed site characterisation, baseline knowledge and a lot of data from the area before a site can be approved,
- Operational and post-closure monitoring are both important,
- Leakage is defined as CO_2 that fluxes across the ground surface and not out of the reservoir,

- Greenhouse gas emissions accounting is concerned with the CO_2 reaching the air or water column,
- More work is needed on deep monitoring methods to help inform the near surface methods in real time,
- The subsurface is known well but operators need to be prepared for any changes
- It is likely and recommended that monitoring programmes will use a variety of technologies that complement one another
- Shallow and surface monitoring may be needed as assurance monitoring,
- Responding to stakeholder concerns is an important facet of monitoring programmes,
- Environmental liability differs in different regions,
- False positives are an important factor to consider when choosing technologies,
- Understanding of post-closure monitoring approaches is still immature,
- Geological CO_2 storage is safe by design, and is designed to be safe.

2021-TR04 Carbon Capture and Utilisation as a Contribution to National Climate Change Mitigation Goals: Japan Case Study report managed by Jasmin Kemper

This report sets out accounting guidelines for measuring greenhouse gas (GHG) emissions and emissions reduction effects arising from technologies involving carbon dioxide capture, utilisation and geological storage (CCUS).

The guidelines apply a project- and product-based approach to measure GHG emission reduction effects, based on comparing the emissions for a CCUS activity with the emissions from a comparable activity delivering the same product or service.

A modular approach is applied. Firstly, users calculate the GHG effects arising from the capture (and transport) of CO_2 based on the avoided emissions from providing the same service or product as output from the CO_2 source facility, but without CO_2 capture.

The resulting estimate of GHG effects from CO_2 capture is carried forward to the utilisation or storage step. In this subsequent step, the GHG emissions from providing the same service without using captured CO_2 is estimated and compared to the GHG emissions of providing the service using captured CO_2. This provides an overall estimate of the cradle-to-gate GHG effect of CCUS activities.

Additional guidance is provided on cradle-to-grave assessment, although this is not the primary focus of these guidelines – the Guidelines focus on annualised GHG emissions accounting cycles rather than whole life emissions analysis.

Specific guidance is provided on:
- Managing system multifunctionality in carbon dioxide utilisation (CCU) activities
- Handling functional equivalence and selecting functional units for CCUS activities
- Managing the risk of CO_2 seepage from geological storage sites.

2021-TR05 Towards improved guidelines for cost evaluation of carbon capture and storage report managed by Keith Burnard

One of the key barriers to the wide scale application of CCS is cost. Understanding the costs of CCS is essential to understand the role for and potential of CCS technology in addressing climate change, and for guidance in research activities aiming to reduce the cost and improve the performance of promising new CCS technologies in different applications. In practice, however, there are many challenges in establishing reliable cost estimates for CCS technologies.

Following the 10th International Conference on Greenhouse Gas Control Technologies in 2010 (GHGT-10), the CCS Cost Network was formed, with a Steering Group comprising experts drawn from industry, government and academia. In 2017, the CCS Cost Network was brought under the aegis of IEAGHG and, since then, has been referred to as the IEAGHG CCS Cost Network. As part of its role as a member of Network's Steering Committee, IEAGHG has helped to organise a series of two-day workshops on costs of CCS.

Following an action from the 2011 CCS Cost Network workshop, a White Paper, entitled "Toward a Common Method of Cost Estimation for CCS at Fossil Fuel Power Plants", was published by IEAGHG and other organisations represented on the Network's Steering Committee. Building on that earlier work, the current White Paper draws up a set of CCS costing guidelines in three complementary areas where further guidelines and better practices are needed, and where efforts are underway to address those topics.

The new White Paper marks a collaboration between workers at several renowned organisations and research institutes. The three areas it covers are:

1. Towards improved cost guidelines for advanced low-carbon technologies

A framework is presented for estimating the future "Nth-of-a-kind" (NOAK) cost of advanced technologies that are currently at early pre-commercial stages of development. The framework distinguishes between two types of question that commonly motivate such a cost analysis: "What If" questions about the hypothetical cost of a technology that meets specified R&D goals; and "What Will" questions regarding the actual expected cost of an advanced technology once it is mature. The latter type of question is of particular interest because of the shortcomings in current methods.

2. Towards improved cost evaluation of carbon capture and storage from industry

Extensive studies have investigated the techno-economic performance of CCS applied to industrial sources, with wide differences in cost estimates observed. While this is due in part to differences in the cases studied and the choice of capture technology, a significant part arises from aspects related to cost assessment methods and assumptions. Building on a previous CCS costing guideline paper , this chapter aims to contribute to the development of improved guidelines for cost evaluation of CCS from industrial applications.

3. Toward improved guidelines for uncertainty analysis of carbon capture and storage techno-economic studies

This chapter reviews and provides guidance on available and emerging methods for uncertainty analysis in CCS techno-economic studies. It is intended to help accelerate continued methods development and their application to more robust and meaningful CCS performance and costing studies, as well as to provide an essential resource for all those developing, communicating and using CCS costing studies.

IEAGHG and Social Media

IEAGHG have a number of publications that are disseminated regularly to the Executive Committee and released into the public forum – including technical reports, technical reviews, information papers and one-off informative publications.

In 2021, 5 technical reports and 5 technical reviews were published (see page 20 for overviews or 34 for the list); two of these reports/reviews were on IEAGHG Network activity.

The IEAGHG Blog

https://ieaghg.org/ccs-resources/blog

The IEAGHG blog, live since December 2011, features both IEAGHG and external contributors, reporting on any and all IEAGHG activities – workshops, network meetings and conferences, promoting to its readers when a new technical report is published and also giving overviews of any significant external events that may be attended by us or our colleagues. The blog is still proving very popular! The Programme published 45 blogs during 2021.

Information Papers

https://ieaghg.org/ccs-resources/information-papers

In 2012, IEAGHG began producing and publishing Information Papers (IPs) as an additional communication tool. These continue to be extremely popular, both with IEAGHG Members and the public. The IPs are short summaries of new research developments in CCS, developments with other mitigation options and summaries of policy activities around the world on low carbon technology, and are an ideal way of satisfying the Programme's broader remit of reviewing all greenhouse gas mitigation options. If there are interesting developments from the IPs we would then undertake a technical review to understand better the issues and the political landscape, then if necessary, propose a detailed study to our members.

The majority of our IPs are free to access and are publicly available as soon as they are published. Occasionally, however, an IP will be deemed 'Confidential' or 'for the Executive Committee only' – in which case the document will not be available to download. We welcome Members and other external parties to submit relevant ideas to be made into an IP. IEAGHG published 29 IPs in 2021.

IEAGHG Social Media

https://twitter.com/IEAGHG
www.linkedin.com/groups/4841998/
https://www.facebook.com/IEAGHG/

The Programme's Twitter, LinkedIn and Facebook pages are thriving and being kept updated and current with regular posts on IEAGHG activities and other relevant news.

Since the publication of the 2020 Annual Review....

2270 Followers (5.5% increase)

facebook

1568 Likes (0.9% increase)

LinkedIn

1195 Group Members (18.5% increase)

IEAGHG Webinars

Webinars have now become a staple in our knowledge sharing cupboard. Each event is recorded and placed on our YouTube channel as an ongoing freely available resource. This year's offerings of webinars can be seen in Table 1 with the number of attendees and the number of YouTube views along with a brief description. Details of our webinars are sent out via our mailing list. If you do not receive our emails, please contact **Tom.Billcliff@ieaghg.org** or signup via http://eepurl.com/du7fkH to be included.

Webinar Title & Description	Date	No. Attendees	No. YouTube Views to Date
High-level analysis of the integration of WtE with CCS/CCU Webinar This webinar looked at the IEAGHG study on CCS on Waste to Energy (WtE). CCS and CCU technologies in WtE plants might have a significant impact on the whole waste industry and global climate commitments. Waste treatment is a traditional sector, driven by regulation and public interest, both ideal for the penetration of CCS/CCU. Waste is processed locally, what places that industry under the objectives of individual governments and single contexts. The objective of this study was to understand some of the issues pertaining to this CCS/CCU opportunity and analyse these at national level.	20/01/21	85	407
Sleipner Benchmark study Webinar CO2DataShare is a digital platform for sharing reference datasets from pioneering CO_2 storage projects. The platform allows researchers based anywhere in the world, to download datasets from representative CO_2 storage sites. In 2020, Equinor which is one of the World's leading companies in the advancement of CO_2 storage, shared its Sleipner 2019 Benchmark model through the CO2DataShare Portal. Each year up to 1 million tonnes of CO_2 from processing of natural gas field is captured and stored at Sleipner. This dataset has provided valuable insights into what happens with CO_2 stored in the subsurface over long periods of time.	25/02/21	78	1084
Biorefineries and CCS Webinar Negative emissions technologies (NETs) feature in many climate models that comply with 2°C scenarios. Efforts to aim towards a 1.5°C target, as outlined in the Paris Agreement, have drawn further attention to the need for options that reduce the overall stock of emissions in the atmosphere. The conversion of biomass feedstocks to biomass-derived fuels and chemicals is referred to as "biorefining". In addition to biofuel, such "biorefineries" typically produce by-products and CO_2. The CO_2 from biomass processing is normally vented to atmosphere but if it were captured and securely sequestered in geological formations (BECCS or Bio-CCS), the produced biofuel could be characterised by net negative emissions because of the storage of biogenic CO_2. In this webinar, Kristian Melin (LUT University, previously VTT Finland) presented the results of a techno-economic assessment (TEA) of biorefinery concepts with and without CCS.	18/08/21	106	145
Review of COP26 Outcomes Webinar COP26 was the most significant COP since Paris in 2015, with important new outcomes. Arthur Lee of Chevron has attended many COPs and follows the negotiations inside UNFCCC closely, particularly on technology issues. He provided his insights on the developments and outcomes from COP26.	02/12/21	76	132

Table 1: List of 2021 Webinars

If there is a subject you would like to see presented, please send ideas and suggestions to Suzanne.Killick@ieaghg.org.

Technical Reports, Technical Reviews, Information Papers and Blogs

Report No.	Technical Report Title	Issue Date
2021-01	Biorefineries with CCS	26/03/2021
2021-02	CO_2 as a Feedstock: Comparison of CCU Pathways	23/11/2021
2021-03	CO_2 Utilisation: Hydrogenation Pathways	16/01/2021
2021-04	Techno-economic Performance, Opportunities, and Challenges of NETs	31/12/2021
2021-05	Global Assessment of DAC	31/12/2021

Table 2: List of 2021 Technical Reports

Review No.	Technical Review Title	Issue Date
2021-TR01	IEAGHG Risk Management Network Webinar December 2020	25/01/2021
2021-TR02	Exporting CO_2 for Offshore Storage – The London Protocol's Export Amendment and Associated Guidelines and Guidance	12/04/2021
2021-TR03	IEAGHG Monitoring Network - 'Monitoring Expertise Showcase for Post-Closure Monitoring'	23/04/2021
2021-TR04	CCUS in national GHG inventories	28/06/2021
2021-TR05	White Paper: Towards improved guidelines for cost evaluation of carbon capture and storage	11/08/2021

Table 3: List of 2021 Technical Reviews

IP No.	Information Paper Title	Author	Issue Date
2021-IP01	UK CCC Sixth Carbon Budget Report	SN	07/01/2021
2021-IP02	WPFE Energy water workshop	MG	08/01/2021
2021-IP03	IEA Key Priorities and Special Projects for 2021	KB	20/01/2021
2021-IP04	ICEF roadmap on biomass carbon removal and storage (BiCRS)	JK	25/02/2021
2021-IP05	UNFCCC Synthesis Report on Nationally Determined Contributions	TD & JL	08/03/2021
2021-IP06	IEA Global Energy Review 2021	KB	26/04/2021

IP No.	Information Paper Title	Author	Issue Date
2021-IP07	CONFIDENTIAL	JC	07/05/2021
2021-IP08	New IEA roadmap: Net Zero by 2050 - A Roadmap for the Global Energy Sector	AL, TD & JK	25/05/2021
2021-IP09	CONFIDENTIAL	TD	11/06/2021
2021-IP10	The Oxford Principles for Net Zero Aligned Carbon Offsetting	SN	01/07/2021
2021-IP11	IEA Report – 'Carbon Capture, Utilisation and Storage: The Opportunity in Southeast Asia'	SN	05/07/2021
2021-IP12	UK BAT Guidelines for Post-Combustion Capture on Power-Plants	KB	12/07/2021
2021-IP13	Blue Hydrogen: Fact vs. Fiction	AA	19/08/2021
2021-IP14	IPCC Working Group I report on the Physical Science Basis of Climate Change 2021	JK & TD	20/08/2021
2021-IP15	Carbon Management and Oil and Gas Research Project Review Meeting	JC	07/09/2021
2021-IP16	CSLF 2021 Technology Road Map	JC	21/09/2021
2021-IP17	Nature article on CDR	JK	11/10/2021
2021-IP18	CONFIDENTIAL	TD	12/10/2021
2021-IP19	UK Net Zero Strategy: Build Back Greener: Synopsis on hydrogen and CCUS	AA	29/10/2021
2021-IP20	Net Zero Strategy and GGRs	JK	29/10/2021
2021-IP21	IEA Global Hydrogen Review 2021	AA	02/11/2021
2021-IP22	IEA: An Energy Sector Roadmap to Carbon Neutrality in China	KB	05/11/2021
2021-IP23	The Global Methane Pledge	SN	05/11/2021
2021-IP24	Net zero electricity in G7	KB	05/11/2021
2021-IP25	Next Generation Capture Technologies	AA	22/11/2021
2021-IP26	NETL Well Integrity Workshop: Identifying Well Integrity Research Needs for Subsurface Energy Infrastructure	JC	29/11/2021
2021-IP27	CONFIDENTIAL	JC	03/12/2021
2021-IP28	Hydrogen for net zero: A critical cost-competitive energy vector	AA	13/12/2021
2021-IP29	CONFIDENTIAL	TD	16/12/2021

Staff Abbreviations:
AA: Abdul'Aziz Aliyu, AL: Arthur Lee, JC: James Craig, JL: Juho Lipponen, JK: Jasmin Kemper
KB: Keith Burnard, MG: Mónica García, SN: Samantha Neades, TD: Tim Dixon

Table 4: List of 2021 Information Papers

Blog Title	Author	Issue Date
The 'Terra Carta', For Nature, People & Planet – Putting Sustainability First	SN	15/01/2021
New IEAGHG report: 2020-06 CCS on Waste to Energy	MG	20/01/2021
GHGT-15 Virtual Conference Registration Now Open	SK	28/01/2021
IEA Workshop on law and regulation for CCUS	TD	01/02/2021
The UK's independent adviser on tackling climate change – webinar on Financing Net Zero	JC	03/02/2021
Heartland US CCUS Forum	SN	04/02/2021
IETA LIVE Series – 'Grounded in Reality: Climate Markets to Scale Carbon Capture, Utilization and Storage (CCUS)'	SN	23/02/2021
US DOE Workshop on Modelling Carbon Capture Technology in the Industrial Sector	KB	24/02/2021
GHGT-15 welcomes attendees worldwide to virtual CCUS conference	TB	16/03/2021
GHGT-15 – Session 3C, Panel discussion 1: 'New business models'	SN	16/03/2021
GHGT-15: Session 7C - Panel Discussion 5: "Closure issues, CA LCFS 100 years and EPA 50 years vs EU performance-based"	SN	17/03/2021
GHGT-15: Session 8C Panel Discussion: Post-Combustion Capture Technology: Progress, Gaps and Future Direction	KB	18/03/2021
GHGT-15: Day 4 Plenary: Update on CCS in China	KB	18/03/2021
GHGT-15: Panel Discussion 4 – CCUS in the Oil and Gas Sector	JC	19/03/2021
GHGT-15: Sessions 1D & 2D – Direct air capture (DAC)	JK	19/03/2021
GHGT-15: Session 3E – Capture in industry	MG	24/03/2021
GHGT-15: Session 1E: Hydrogen & CSS	MG	25/03/2021
New IEAGHG Technical Report: 2020-01 Biorefineries with CCS	JK	26/03/2021
Policy and Regulatory Summaries from GHGT-15	TD	29/03/2021
IEA-COP26 Net-Zero Summit Virtual High-Level Dialogue	KB	08/04/2021
CEM CCUS Initiative: Environmental, Social and Governance (ESG) Assessments and CCUS	SN	19/04/2021
New IEAGHG Report: IEAGHG Monitoring Network – Webinar & Virtual Discussion: Monitoring Expertise Showcase for Post-Closure Monitoring, 2021-TR03	SN	23/04/2021
Are we finally mainstreaming CCUS?	JL	10/06/2021
A quick look at the G7 agreements – "Build Back Better"	TD	14/06/2021

Table 5: List of 2021 Blogs

Blog Title	Author	Issue Date
TCCS-11 goes virtual	TD	23/06/2021
New IEAGHG Technical Review: Carbon Capture and Utilisation as a Contribution to National Climate Change Mitigation Goals: Japan Case Study	JK	28/06/2021
New IEAGHG Technical Review: Towards improved guidelines for cost evaluation of carbon capture and storage	KB	11/08/2021
2021 ITB-IAGHG Virtual CCUS Course	SN	17/08/2021
IEAGHG-IPA Pre-Convention Short Course on CCUS for Executives	SN	20/08/2021
IPCC Working Group I report on the Physical Science Basis of Climate Change 2021	JK	20/08/2021
UKCCSRC 2021 Conference 'Delivering on COP26: CCS across the World', 7th and 8th September	JC	10/09/2021
IEA Workshop on CCUS for Nigeria's Energy Transition	TD	17/09/2021
IEAGHG's GHGT conference helped stimulate the concept of BECCS	TD	11/10/2021
U.S. DOE Workshop on Modelling and Analysis of Energy Challenges to Meeting U.S. 2050 Goals	AA	13/10/2021
Asian Development Bank Workshop on De-Carbonization of Cement Sector through CCUS	AA	19/10/2021
UK CCUS Cluster projects: two given go-ahead, and details of all clusters provided at CCSA Conference	JC	19/10/2021
COP26 starts in Glasgow	TD	02/11/2021
"Net Zero World" Initiative	TD	05/11/2021
US launches two initiatives on CDR	TD	08/11/2021
Shell Catalysts & Technologies webcast on accelerating a sustainable recovery: Carbon Capture and Storage	AA	09/11/2021
Shell Catalysts & Technologies webinar on accelerating a sustainable recovery: Hydrogen technologies	AA	09/11/2021
CCS Side-events in the second week of COP26	TD	12/11/2021
COP26 and the Glasgow Climate Pact	TD	15/11/2021
New IEAGHG report: 2021-03 CO_2 Utilisation: Hydrogenation Pathways	JK	16/11/2021
New IEAGHG report: 2021-02 CO_2 as a Feedstock: Comparison of CCU Pathways	JK	23/11/2021

Table 6: List of 2021 Blogs (Continued)

Staff Abbreviations:
AA: Abdul'Aziz Aliyu
JC: James Craig
JK: Jasmin Kemper
JL: Juho Lipponen
KB: Keith Burnard
MG: Mónica García
SN: Samantha Neades
TB: Tom Billcliff
TD: Tim Dixon

IEAGHG Presentations Made in 2021

Date	Meeting Title	Presentation Title	Speaker
20/01/2021	IEAGHG webinar	High-level analysis of the integration of Waste-to-Energy with CCS/CCU	MG
24/02/2021	KAUST Conference 2021	Prospects for the development of Geothermal Energy and CCS with potential application to the Kingdom of Saudi Arabia	JC
31/05-04/06/2021	CEM 12 Chile	CCUS 101	TD
01/06/2021	Indonesia	Carbon Capture, Utilisation and Storage (CCUS) – Regulation and Carbon Accounting	TD
10/06/2021	Enfield 2021	Carbon Capture and Storage (CCS)	TD
07/07/2021	OPEC 4th Technical Workshop	The role of the Circular Carbon Economy and 'Green Initiatives' in combating Climate Change	JC
28/07/2021	Considerations for CCUS Projects under Article 6	IEA / CEM CCUS Workshop on International Finance Mechanisms	TD
04/08/2021	DOE-NETL 2021 Carbon Storage Project Review Meeting	An International Update on CCUS from IEAGHG	TD
10/09/2021	IEA-OVP workshop on Facilitating Nigeria's Energy Transition through CCUS Development	Status of CCUS	TD
26/10/2021		North Sea CCS Clusters	JC
27/10/2021	SAKURA meeting	Introduction to IEAGHG	JC
17/11/2021	COP26	COP26 Update	TD
26/11/2021	Geosciences Technology Workshop - High CO_2, High Contaminant Challenging Fields and Alternative Energy - Impact and Monetization (A Joint Workshop with EAGE)	Providing CCUS skills for a sustainable Energy Future	TD

Staff Abbreviations:
JC: James Craig MG: Mónica García TD: Tim Dixon

Table 6: List of 2021 Presentations

Members of the Programme

AUSTRALIA
Dr Paul Feron (M)
Dr Kelly Thambimuthu (Chairman)

AUSTRIA
Mr Theodor Zillner (M)
Dr Gunter Simader (A)
Mr Ernst Goettlicher (A)

CANADA
Dr Eddy Chui (M)

EUROPEAN COMMISSION
Dr Vassilios Kougionas (M)
Mr Jeroen Schuppers (A)

FINLAND
Jussi Mäkelä (M)
Elina Maki (A)
Elke Schnabel(A)

FRANCE
Isabelle Czernichowski (M)
Alix Bouxin (A)

INDIA
Dr Atul Kumar (M)

JAPAN
Mr Ryozo Tanaka (M)
Hiroto Yoshikawa (A)
Dr. Ziqui Xue (A)

KOREA
Jeom–In Baek (M)

NEW ZEALAND
Mr Rob Funnell (M)
Mr Mark Pickup (A)

NETHERLANDS
Gerdi Breembroek (M)
Martijn van de Sande(A)

NORWAY
Dr Åse Slagtern (M & VC)
Mr Hans Jorg Vinje (A)

OPEC
Dr Eleni Kaditi (A)
Ms Angelika Hauser (A)
Dr Mohammed Ali Zarie Zare (M)

SOUTH AFRICA
David Khoza (M)
Mr Thulani Maupa (A)

SWEDEN
Svante Soderholm (M) | Isabella Gustafsson Ismodes (A)

SWITZERLAND
Valentin Gischig (M) | Dr Sophie Wenger (A)

UNITED KINGDOM
Mr Will Lochhead (M) | Hannah Lord (A)
Carly Leighton (A) | Treasure Udabor (A)

USA
Mr Mark Ackiewicz (M & VC) | John Litynski (A)
Anhar Karimjee (M) | Jeff Hoffman (A)

Baker Hughes
Dr. Alex Cruz (M) | Ms Allyson Anderson Book (A)

BP
Martin Towns (M) | Tony Espie (A)

Chevron
Mr Arthur Lee (M)

CIAB
Mr Peter Morris (M) | Mr Mick Buffier (A)
Karl Bindemann (A)

EPRI
Mr Robert Trautz (M)

equinor
Peter Zweigel(M) | Mr Henrik Solgaaard Andersen (A)

ExxonMobil
Mr Ganesh Dasari (M)

JÜLICH FORSCHUNGSZENTRUM
Eric Busche (M)

Eduardo Preciado (M)
Dr Antonia Diego Marin (A)

Bandung Institute of Technology

Prof. Dr. Warwan Guna A Kadir
Dr Mohammad Rachmat Sule

Ms. Aiko Horikawa (M)
Mr Tsukasa Kumagai (A)

Seiji Hongo (M)
Shinichi Sakuno (A)

Tilman Bechthold (A)
Karl-Josef Wolf (M)

SHELL

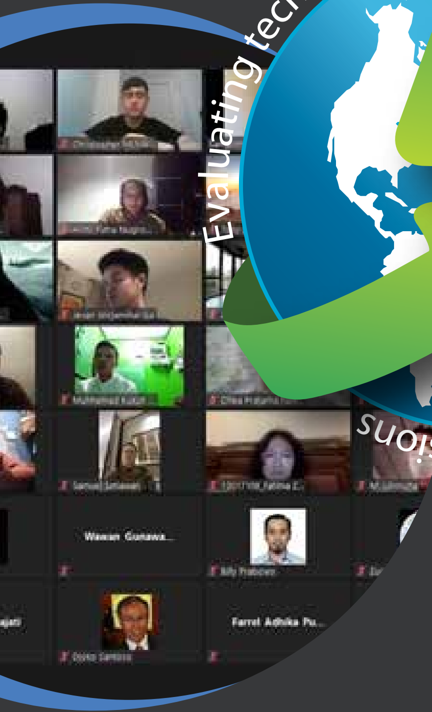
Dr Owain Tucker (M)

Gianni Serra (M)

Richard Esposito (M)

Stanislas Vanderberg (M)
Philip Llewellyn (A)

Samantha McCulloch



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