Evaluating technology options to mitigate greenhouse gas emissions

annual review 2020

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

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Inside Cover Image: National Carbon Capture Center, Wilsonville, Alabama, USA. Image courtesy of Southern Company.
Front and Back Cover Images: 4th International Workshop on CCS delegates visiting the proposed CCS Base hub location at Kollsness; Abu Dhabi at night, host city for GHGT-15; Presentations from IEAGHG Risk Management Network Webinar & Discussion Panel, August 2020; National Carbon Capture Center, Wilsonville, Alabama, USA; Attendees at the 8th High Temperature Solid Looping Cycles Network, Geleen, The Netherlands, January 2020; Attendees of the 4th International Workshop on Offshore Geologic CO_2 Storage, Bergen, Norway, February 2020.

Annual Review Contents

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

Chairman's Message

2020 ties as warmest year on record.

With all the official climate data now in, the world's surface temperatures in 2020 have been confirmed as effectively tied with 2016 as the warmest year on record. In summary, 2020 saw: record warm surface temperatures, record levels of ocean heat, record warmth in the troposphere, record lows in summer arctic sea ice and record sea level rise.

Our colleagues in the International Energy Agency have released several major reports in 2020, most notably the Energy Technology Perspectives 2020 and the Special Report on CCUS. These emphasise the urgency of mitigation of CO_2 from the energy sector, and show the means of achieving it, noting that decarbonising electricity supply is not enough on its own.

A key aspect is on decarbonising existing energy assets during their lifetime, and CCUS is the leading solution to that problem with its ability to be retrofitted. CCUS is also key to enabling the provision of low and no carbon hydrogen, which then can decarbonise the hard-to-reach sectors of transport and industry. Whilst CCUS can be deployed now, the role for further innovation is also emphasised by IEA, and IEAGHG is a major contributor to this and its role of actively facilitating international collaboration.

Interest increases in negative emission technologies for greenhouse gas removal from the atmosphere. CCUS is a key component of negative emission technologies, and IEAGHG is increasing its coverage of those technologies accordingly.

In 2020 we saw the world facing drastic new challenges with the COVID-19 pandemic, and as with climate change, science and technology are providing the solutions. But, as with climate change, it needs us, the people, to put the solutions into practice. The COVID-19 response has shown how we can respond collaboratively to one global emergency. It is indeed both a lesson and an opportunity on how we should tackle the greatest existential crisis that we face – climate change.

Kelly Thambimuthu at GHGT-14, Melbourne

Kelly Thambimuthu,
Chairman of the IEAGHG Executive Committee

General Manager's Summary

To say that 2020 was a year of challenges is an understatement.

I would like to think that IEAGHG rose to the challenges within its remit, and without pause continued to deliver reports, virtual meetings, information papers and blogs, driven by our great team of enthusiastic and innovative staff. We were very pleased with the number of technical reports we published (17), two virtual members meetings, two virtual network meetings, and our successful series of technical webinars.


Tim Dixon, IEAGHG General Manager

We saw the results of our work being used by the International Energy Agency in several major reports issued in 2020, most notably the Energy Technology Perspectives 2020 and the Special Report on CCUS. Both of these are influential. It was disappointing to have to not hold physical meetings. We managed to get two in before COVID restrictions, the High Temperature Solid Looping Cycles Network in The Netherlands and the 4th Offshore CCS workshop in Norway (with the University of Texas). Most of all, it was painful to have to postpone GHGT-15 to 2021, with all the hard work done in selecting a high-quality technical programme representing so much work by CCS experts around the world. However, we have been able to retain that high quality technical programme and making it fully virtual in 2021 is an exciting first for us and the hosts Khalifa University. As we postponed our Network meetings, we moved aspects of them into the virtual world with apparent success. Both the Monitoring Network and the Risk Management Network held virtual meetings.

We had to postpone our International CCS Summer School, which would have been hosted by Bandung Institute of Technology (ITB) in Indonesia. Instead, we worked with ITB in providing a virtual course on CCS over two weeks aimed at ASEAN-OCEANIA students.

Our usual technical webinar series continued. I was particularly pleased with the webinar on water usage and CCS, which brought together early IEAGHG work on reducing water-use in capture facilities, with the latest work combining water aspects of both storage and capture to reduce net water-usage to zero.

It was a pleasure to see the Norwegian government proceed with the Longship project, including Northern Lights, which was enabled by the removal of the export barrier in the London Protocol in which IEAGHG played a role. IEAGHG are located in the UK, and with great interest we saw the UK government ramp up its CCUS plans along with its emissions reduction target of 68% by 2030 in its updated Nationally Determined Contribution to the Paris Agreement.

Whilst COP26 was postponed to 2021, it was very encouraging to see so many countries making net-zero pledges, and especially the UK with the detailed plan on how to get there from its Climate Change Committee. It is without question that CCUS has a major role to play in achieving net-zero, and we all must work hard to help deliver it. And all the time climate change continued. 2020 was the joint warmest year on record (with 2016) even though CO_2 emissions were estimated to fall by nearly 8%. We hope the key reports from the International Energy Agency have a suitable influence on countries as the world seeks to recover from the impacts of COVID-19 and 'build back better'.

Tim Dixon,
IEAGHG General Manager

Key IEAGHG Achievements in 2020

External Presentations by IEAGHG Staff

14 Technical Reports
3 Technical Reviews
25 Information Papers
4 Briefing Papers

Meetings

8th High Temperature Solid Looping Cycles Network (HTSLCN) Meeting
Over 30 attendees

Monitoring Network Virtual Discussion Panel
Over 70 attendees

Risk Management Network Webinar & Discussion Panel
Over 60 attendees

4th International Workshop on Offshore CCS
Over 150 attendees

CCUS Virtual Course for Asia-Oceania Region
80 Students

Published to Online Media

5 Webinars
896 YouTube views

Page Views: 79, 216

Views of IEAGHG Website: 39, 354 Sessions

IEAGHG Operations Report

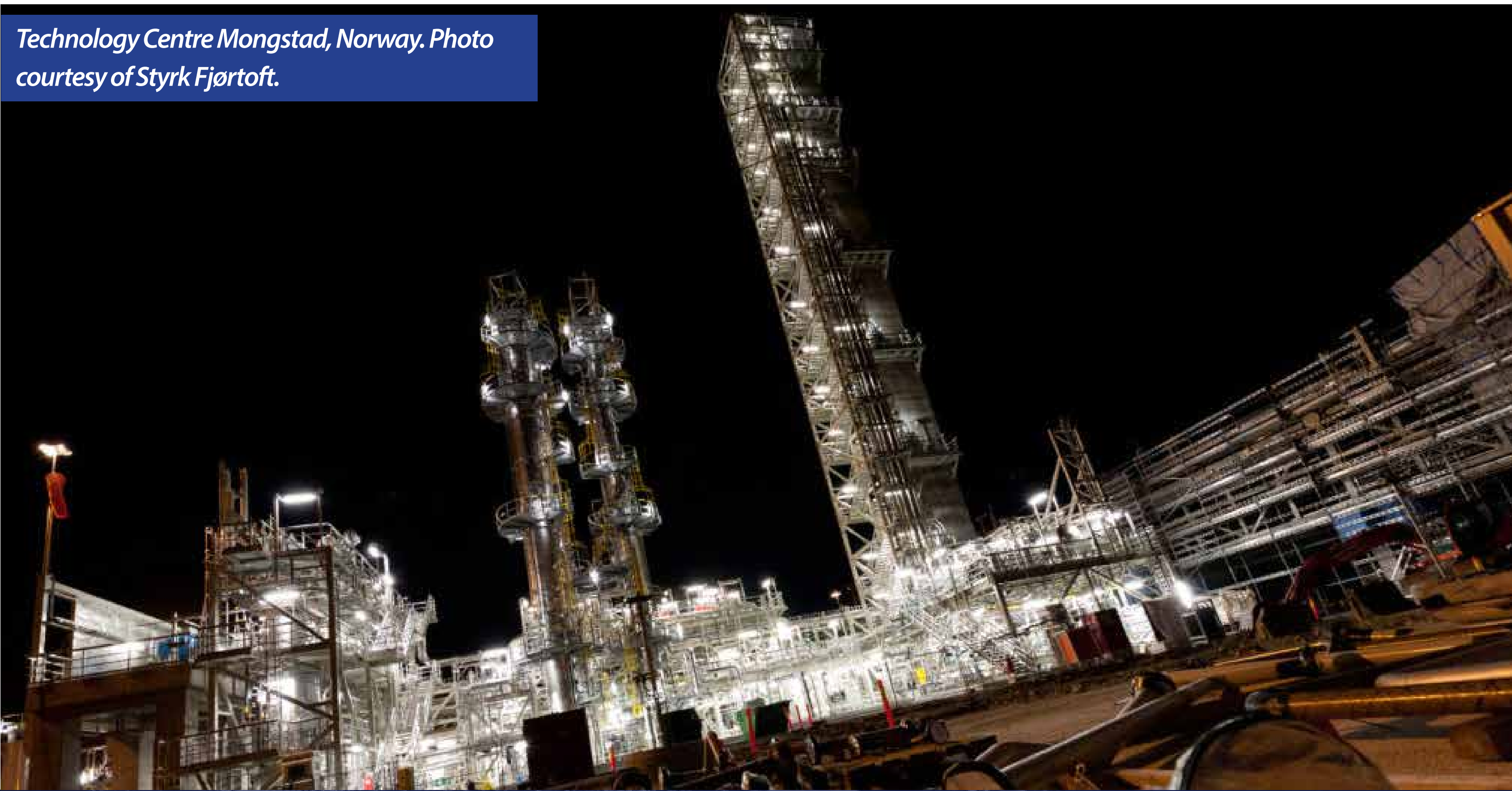
Membership increased in 2020 to 37 members. We welcomed Baker Hughes to IEAGHG. Our total annual income was approximately £1.6m, and the budget was allocated as illustrated below.

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 accounts are available to members.
Note 2: COVID reduced some of the final expenditure on travel and meetings.

Technology Centre Mongstad, Norway. Photo courtesy of Styrk Fjørtoft.



Facilitating Implementation

IEAGHG helps to facilitate the implementation and deployment of CCS by contributing the technical evidence-base to policy-makers 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 implementation and deployment. 2020 was a challenging year because COVID meant that many of the usual meetings were postponed to 2021.

UNFCCC COP26

COP26 was due to be held in Glasgow in the first two weeks of December 2020, but was postponed to 1st-12th November 2021. This meant that the details of Article 6 of the Paris Agreement remain to be agreed. For IEAGHG, our primary focus would have been organising the UNFCCC Side-event with our collaborators the University of Texas, the International CCS Knowledge Centre and CCSA.

For the last six COPs we have organised the only UNFCCC Side-event focussed on CCS. We were able to provide our members with a webinar in January 2020 to review the outcomes of COP25. IEAGHG monitored the various UNFCCC virtual events over 2020 for any significant developments, and presented some reflections as "One Year to COP26" at the CCSA's CCUS2020 virtual conference.

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 early 2020 IEAGHG provided 31 Expert Review comments to the First Order Draft (FOD). The Second Order Draft is expected in early 2021.

London Protocol

IEAGHG has been reporting to our members from the London Convention meetings (the UN-based global treaties that protect the marine environment) for over thirteen years by attending and reporting by Information Papers and blogs, as the only CCS-related organisation attending in recent years.

The 2020 annual meeting, LC42/LP15, was moved to 14-15 December 2020, virtual format. The CCS agenda item was postponed to the 2021 meeting, so there was not the usual opportunity to provide an update from IEAGHG on activities relating to offshore CCS.

After the successful achievement in 2019 with the CCS export resolution, IEAGHG published the full text of the "Resolution LP.5(14) on the Provisional Application of the 2009 Amendment to Article 6 of the London Protocol" from the LC41/LP14 annual meeting report, as IEAGHG Information Paper 2020-22. Over 2020, IEAGHG monitored developments with use of the CCS export resolution. IEAGHG also agreed to co-author a paper with the International Maritime Organisation (the secretariat for the London Protocol) for GHGT-15 to make more accessible the details of CCS export resolution and associated guidance from the London Protocol.

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 2020 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 for publishing in 2021.

The series of International Workshops on Offshore Geologic CO_2 Storage were initiated by Bureau of Economic Geology (BEG) and organised with IEAGHG in response to recommendations made by a CSLF Task Force report on offshore CCS in 2015. In 2020, the 4th International Workshop on Offshore Geologic CO_2 Storage was held in Bergen and is reported on page 10.

ISO TC/265

This ISO committee was proposed by Canada and set up in 2012 with a Canadian Chair and Canadian and Chinese Secretariat. There are 20 participating countries, 10 observing members, and 7 Liaison organisations including IEAGHG.

It consists of six working groups: WG 1 Capture (lead by Japan); WG 2 Transport (lead by Germany); WG 3 Storage (lead by Canada and Japan); WG 4 Quantification and Verification (lead by China and France); WG 5 Cross-cutting issues (lead by France and China); WG 6 CO_2-EOR (lead by USA and Norway). IEAGHG is a Liaison Organisation to TC265, and is a member of WG 3 and WG5.

The last plenary was held virtually from the 1st – 5th June 2020. IEAGHG provided an update.

4th International Workshop on Offshore CCS

Some 150 participants attended the 4th International Workshop on Offshore Geologic CO_2 Storage which was held jointly with the STEMM-CCS Open Science Meeting, and hosted by the University of Bergen, over 11-13 February.

4th International Workshop on Offshore Geologic CO_2 Storage, Bergen, February 2020

The Offshore workshop series was initiated by the University of Texas Bureau of Economic Geology (BEG), and organised jointly with IEAGHG. This fourth workshop addressed and built on the recommendations from the third workshop, continuing the theme of 'How to do'. It was observed that the recommendations from the third workshop had been acted upon by IEAGHG, BEG and others. The fourth workshop covered infrastructure, deep monitoring and modelling, regulatory frameworks, project updates from some 12 projects around the world, emerging CCS country needs and progress, a global sum-up, and brainstorming towards an international collaborative project. Updates were given on project activities in Norway, Brazil, Japan, USA, The Netherlands, UK, Australia, Trinidad and Tobago, Korea, Taiwan and the Baltic. In usual IEAGHG-style, the workshop ended by drawing conclusions, key messages, and recommendations from all the presentations, updates and discussions.

A key conclusion identified the benefits for CCS deployment in learning from hydrocarbon activity knowledge, including significant cost reductions, especially with examples from Northern Lights. It was also recognised that many more offshore projects are now being planned or investigated, and that many of these are considering hubs with phase-in of sources, hence needing to oversize transport infrastructure at the start, and recognising that now CO_2 can be exported thanks to the London Protocol. A technical aspect from several projects was around depleted fields having the challenge of pressure drop from well head to reservoir, hence needing management of CO_2 temperature. Based on industry project perspectives, it was emphasised that monitoring, measurement & verification (MMV) costs can be reduced by MMV strategies being risk-based and with a 'tiered' approach.

Recommendations included to continue information sharing, such as with these workshops, the exchange of experiences, and getting more developing countries to these meetings. An important recommendation was regulatory, for authorities to consider re-use of infrastructure before requiring decommissioning. All recognised the great potential for offshore CCS, and the need to communicate this to governments and other stakeholders. As Nationally Determined Contributions (NDCs) under the Paris Agreement get updated, more countries will need to included CCS in them, so to make countries aware of their own potential for offshore CO_2 storage or potential for export to neighbouring countries with offshore CO_2 storage. The CCS community would benefit from having offshore sites to practice monitoring and learn from.

On the final day a good number of the attendees were hosted by Equinor, learning more about the CO_2 DataShare initiative for sharing seismic data from operational projects for modellers to use, and more detail about the Northern Lights project's geology and site. This day concluded with a site visit to Northern Lights project's proposed CO_2 hub, called "CCS Base", at Kollsness. This was thought to be the first international group to visit this proposed location for the CO_2 receiving and transport hub. The global significance of this potential hub was appreciated by all attending, with the implications for stimulating CO_2 capture from many industrial sources in Europe.

The report of the fourth Offshore CCS Workshop is available as IEAGHG 2020-TR02, and ppts are available on the BEG website. Many thanks to the STEMM-CCS project and the University of Bergen for hosting and sponsoring, and CLIMIT for sponsoring, and CSLF for supporting developing country delegates.

The STEMM-CCS sessions conveyed a lot of results from this remarkable project funded by the EU Horizon 2020 programme. Central to the project was the controlled release experiment, the first sub-seafloor release of CO_2 to be carried out under real life conditions and water depths, implemented at a site near the Goldeneye platform in the North Sea. The results are shared in detail in more than twenty papers going to a Special Issue of the IJGGC. For more information and summary of the results, see https://www.stemm-ccs.eu/. IEAGHG was honoured to chair the STEMM-CCS Stakeholder Advisory Board.

4th Workshop delegates visiting the proposed CCS Base hub location at Kollsness

8th High Temperature Solid Looping Cycles Network (HTSLCN) Meeting

The high temperature solid looping cycles (HTSLC) network meeting covers technology developments in fields where a solid material is cycled between multiple reactors at elevated temperatures.

Attendees at the 8th High Temperature Solid Looping Cycles Network, Geleen, The Netherlands, January 2020

The scope of the IEAGHG HTSLCN is to discuss recent progress in solids looping cycles such as calcium looping and sorption enhanced reforming for selective CO_2 transport and chemical looping combustion (CLC) and reforming with selective oxygen transport by the solids. It brings together well-known technologies used in fluid catalytic cracking, circulating fluidized beds (CFB) and combined cycles (CC), in new ways, to increase efficiencies and provide opportunities to decrease the carbon-footprint of energy intensive processes.

The 8th HTSLCN Meeting took place recently from 20th to 21st of January 2020 at Chemelot Industrial Park, in Geleen, The Netherlands, hosted by TNO in collaboration with the CLEANKER and LEILAC projects. 30 attendees enjoyed a two-day programme with a total of 16 presentations and a site visit to the LEILAC demonstration plant in Lixhe, Belgium.

The first day started off with a welcome from the organisers TNO and IEAGHG. The first session was about CLC and contained presentations on the CLARA project (which investigates chemical looping gasification (CLG) for biofuel production), the assessment of natural ores and industrial wastes for CLG, the integration of pumped thermal energy storage fuelled by CLC with an open cycle gas turbine (OCGT), and a techno-economic assessment of a packed bed reactor for chemical looping reforming (CLR). The second, and last, session was all about Calcium looping (CaL) processes.

The session started with presentations about two projects: BREIN-STORM (which explores high temperature solid looping processes in the steel industry) and HyPER (which investigates bulk hydrogen production by sorption enhanced reforming (SER)). The attendees were also informed about the flexibility of a circulating fluidised carbonator in a 1.7 MWth CaL pilot plant, integration of an indirectly heated CaL process in lime and cement plants, CaL systems with thermochemical energy storage and the application of CaL in waste-to-energy (WTE) plants.

The second day started with a dedicated session on the CLEANKER project (CLEAN clinKER production by CaL process). The first presentation provided an overview of the project, which aims at demonstrating the Calcium Looping (CaL) concept at TRL7 in a configuration highly integrated with the cement production process, making use of entrained flow reactors. The demonstration plant will capture CO_2 from a portion of the flue gas of a cement plant in Vernasca (Italy) operated by Buzzi Unicem.

The rest of the session then dealt with the characterisation of the cement raw meal that is used as CO_2 sorbent, the calcination kinetics and the modelling, engineering and construction of the demonstration plant. In the afternoon, the attendees of the 8th HTSLCN Meeting were then able to visit the LEILAC (low emissions intensity lime and cement) demonstration plant in Lixhe, Belgium. The project's aim is to assess whether direct separation calcining technology can work at the higher temperature required and will capture over 95% of the process CO_2 emissions.

Concluding from the technical sessions and the wrap-up session, it was noted that a lot of the hot topics identified during the panel discussion of the last meeting are being addressed now. Two examples for this are the flexibility of solid looping systems and achieving negative emissions with solid looping systems by using biomass. Questions and uncertainties regarding the use of CaL for coal fired power plants in Europe remain due to the phase-out of these plants. This has caused a shift to industrial applications, which offers a vast research, development & demonstration (RD&D) landscape for solid looping systems.

More information on the HTSLCN and its activities can be found on the IEAGHG website www.ieaghg.org, including a combined report of the most recent HTSLCN meetings.

IEAGHG Monitoring Network Virtual Discussion Panel: 'Regulation, Industry and Research - Translating Monitoring Research to Meet Commercial Needs'

This webinar and virtual discussion panel was held on Wednesday 12th August 2020 at 10pm BST with the theme of informing regulators, looking at 'Regulation, Industry and Research - Translating Monitoring Research to Meet Commercial Needs'.

Panellists on the IEAGHG Monitoring Network Webinar, August 2020

The panellists comprised different CO_2 storage monitoring stakeholders; operators, regulators and researchers and attendees were asked to submit questions for the panellists to consider prior to the event, of which over 120 were received.

The aim of the panel was to discuss the translation of CO_2 geological storage monitoring research into regulations and commercial-scale projects. It began with a scene setting presentation and framing questions with in-depth and thoughtful discussion with operator, regulator and research representatives from the US, Australia and Norway.

Over 60 external attendees sat in to listen to the 8 panellists on the panel, which was an ideal opportunity for all stakeholders actively engaged in CO_2 geological storage projects and practical research in monitoring to share and learn about how the information from research and our Monitoring Networks can be used to meet commercial needs.

The panellists discussed a series of topics throughout the event, provoking thoughtful and interesting discussion:

- Evolution of monitoring storage sites from R&D to commercial projects; where are we now and how does R&D, learnings & regulation feed into this current status?
- Where have the greatest improvements in monitoring technologies in the last ten years been from a technical and regulatory perspective?
- What are the best approaches and limitations on translating monitoring progress in one country to another?
- Monitoring is often considered critical for obtaining the social license-to-operate; do you agree and how much monitoring is needed to meet this?
- The cost of CCS remains a barrier; how does the cost of monitoring enter into this?
- What approach (in terms of need for, duration & type) in monitoring is recommended to develop best practices?
- To improve monitoring in CCS, what is needed in the near term and the longer term?

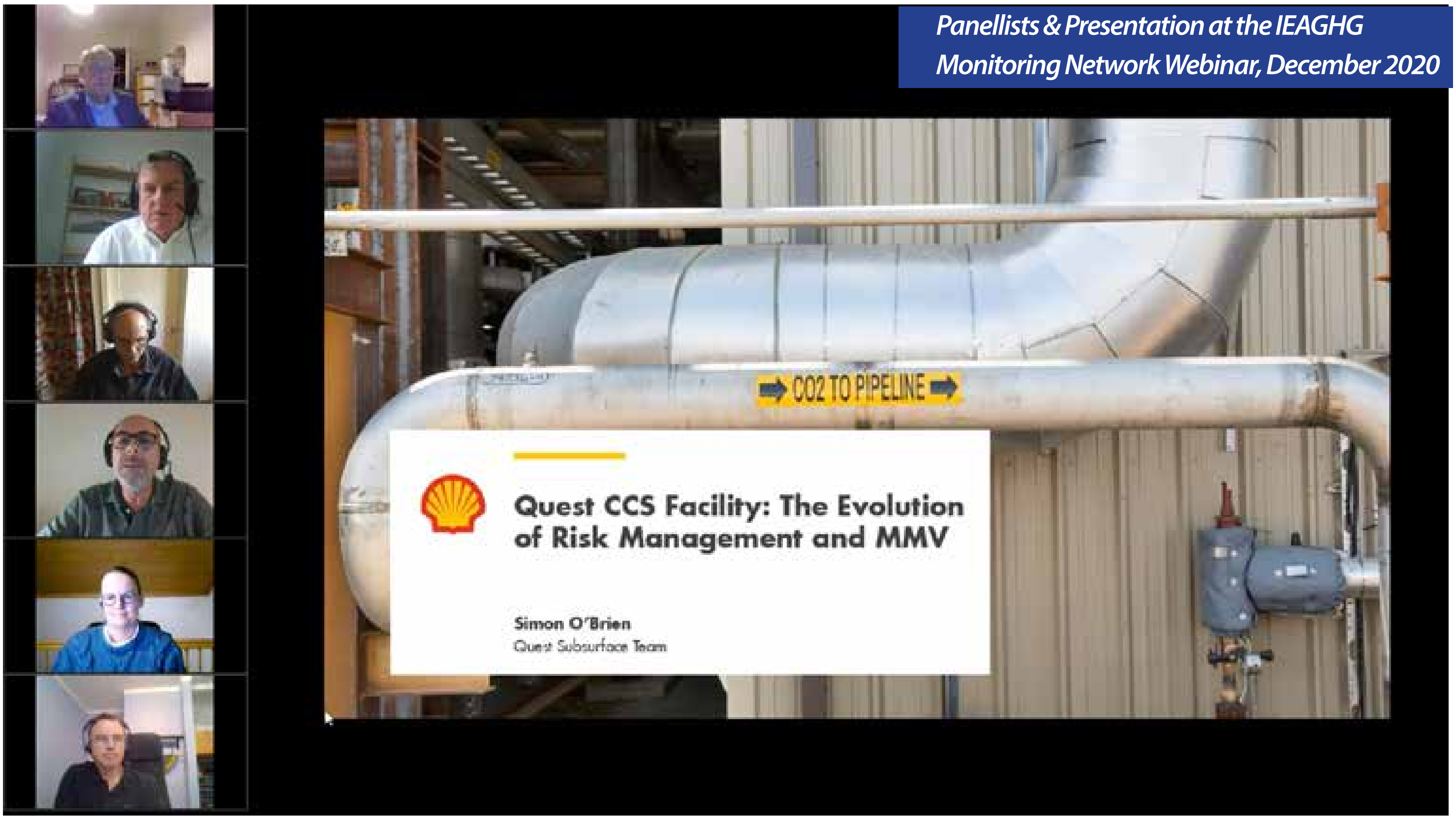
The key conclusions drawn from the conversation included:

- More should be done to reduce costs and improve the cost efficiency of monitoring techniques,
- Regulators rely on operators to propose a monitoring strategy and techniques suitable for the site,
- Regulators are strong believers in objective-based regulation rather than prescriptive-based regulation,
- Regulators prefer monitoring techniques which are tried and tested, but encourage monitoring R&D on demonstration sites,
- Some of the greatest developments in monitoring over the last ten years are the development of DAS and distributed temperature sensing along with permanent surface seismic sensing, and near-surface attribution monitoring, to improve monitoring efficiency,
- Practices and processes need to be harmonised with international collaboration and shared learning to allow projects to move forward,
- Public perception and acceptance is key and it's important to inform the public on the reasons as to why we are undertaking CCS, why we are injecting the CO_2 for safe storage; the importance of meeting emissions reductions targets and the need for CCS,
- It is crucial to have the capabilities to respond to any stakeholder concerns that may arise and therefore there is a need for contingency monitoring,
- Every site is unique in terms of its geology, project specifics and stakeholders, so monitoring techniques and strategies will be used differently at different sites,
- Projects should be encouraged to use the power of available and applicable standards as part of their dialogue with regulators to move away from time-based to performance-based criteria,
- More practice is needed with failure scenarios.

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 2020-TR03.

IEAGHG Risk Management Network Webinar & Discussion Panel: 'Risk Management Over Time at Operating and Future CCS Projects'

The IEAGHG Risk Management Network held a webinar aimed at those involved and interested in the risk management of CCS projects on the 2nd December 2020, which was attended by 59 audience members, 6 expert panellists and 4 IEAGHG staff.



Panellists & Presentation at the IEAGHG Monitoring Network Webinar, December 2020

The webinar kicked off with a talk from the operators of the Canadian Quest project, Shell, who provided a view of the project's risk management process and how it has evolved over time, from project inception to commissioning, operation and post-injection. Following this informative and in-depth presentation from Shell, the panel discussion dove into engaging discussions on a number of key topics from the perspectives of leading CCS developers, researchers in CCS and project operators.

A number of key questions were used by the moderator to help shape the conversation:

- Do current risk management approaches need to be adapted to larger scale; does bigger storage mean riskier projects?
- Are the biggest risks before, during or after a CO_2 injection project?
- Do public stakeholders have realistic or exaggerated perceptions about storage risks, and how should these be addressed?

- How do you communicate to stakeholders how you quantify risk?
- What about the level of expertise and / or understanding of CO_2 storage operations in government regulatory bodies – are governments ready for CCS?
- What level of monitoring is required to satisfy a project?
- In view of the evolution of risk management, what is the most significant improvement (tool or methodology) in the risk management process?

The key messages drawn from the discussion were:

- 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 arise where people do not understand specific technologies or understand the complexity of risk management practices,
- It is critical that projects 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 community,
- 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.

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-TR01.

CCUS Virtual Course for Asia-Oceania Region

The 2020 IEAGHG CCS Summer School was due to be hosted by Institut Teknologi Bandung (ITB), in Indonesia, but was postponed due to COVID-19. Instead, IEAGHG worked with ITB to create a virtual CCS course. This was held from the 9th to the 20th November 2020, hosted by ITB and co-hosted by IEAGHG.

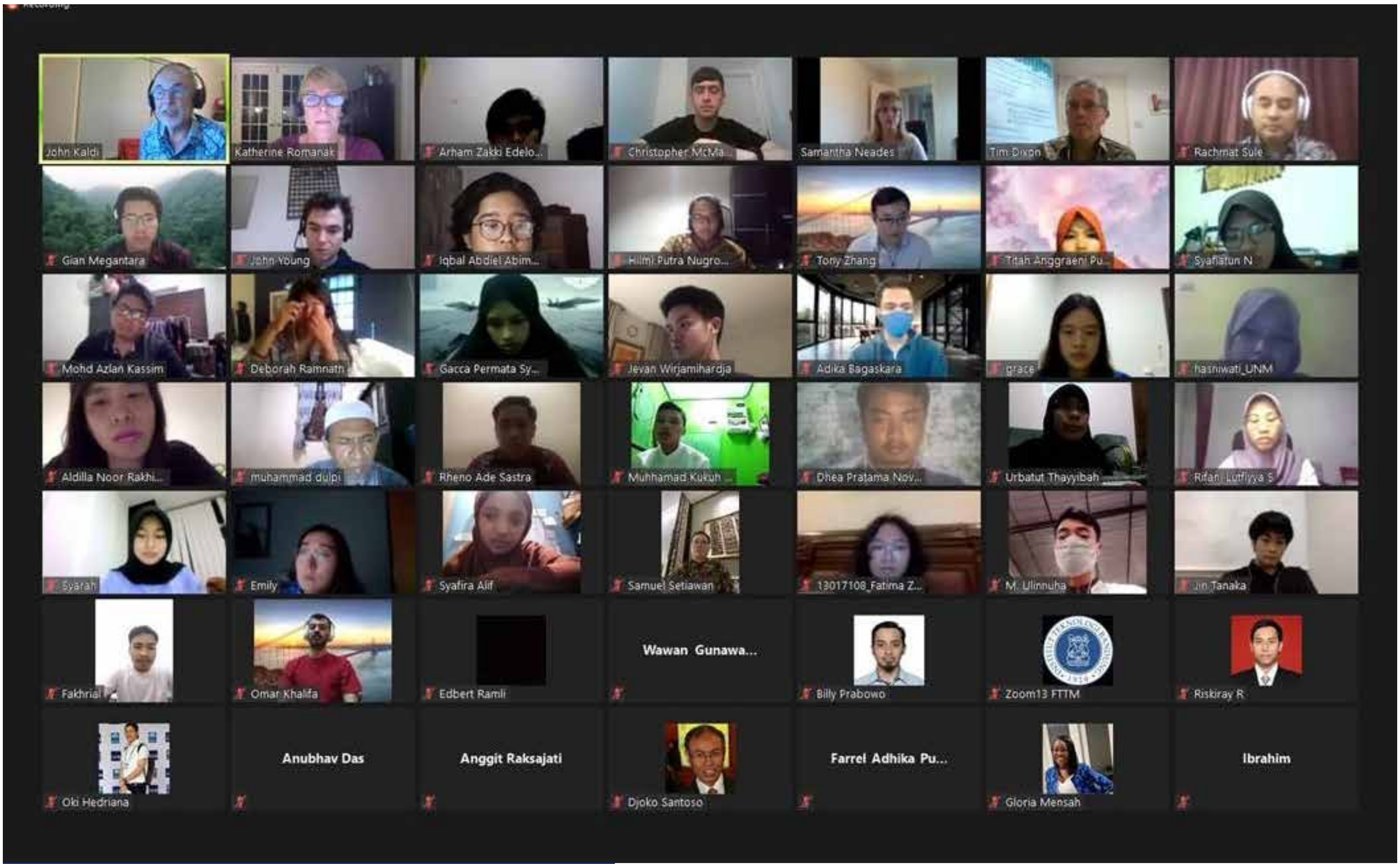
This two week online course was the first in a series of learning events held by ITB at the end of 2020 to continue facilitating learning for students during these virtual-centric times and also to celebrate the centenary year of the university. The courses were opened in a special ceremony streamed live on the 6th November and students and teachers involved in all of the events were welcomed by Professor Reini Wirahadikusumah, Rector of Institut Teknologi Bandung.

The virtual course on CCUS was open to BSc and MSc students in the areas of geology, geophysics, petroleum engineering, chemical engineering and mechanical engineering specifically in the Asia-Oceanic region; although international students who have been accepted onto the 2020/21 IEAGHG International Summer School were also extended an invite.

In total, 80 eager students registered for the virtual CCUS course and the lectures were given by ITB faculty and by other experts from the USA, Canada, Norway, UK, France, Austria, Japan, India, Singapore and Australia, drawing upon IEAGHG Summer School lecturers. The lecture programme itself was based upon the IEAGHG International Summer School programme and covered all aspects of the CCUS value chain, from capture to storage and from BECCS to NGO perspectives. Following the event, students were invited to gain official credits for this course by submitting a short essay on 'Is CCS appropriate for your country, and how would you implement it?'

IEAGHG would like to thank the hosts of the virtual course, ITB for their hard work in facilitating and organising the event, and the valued speakers who provided their time in providing the students the lessons. The course was supported by speakers from the University of Adelaide, CO2CRC, Pertamina University, National University of Singapore, University of Nottingham, the International CCS Knowledge Centre, IIASA, I2CNER at the Kyushu University, RITE, Total, ExxonMobil, Shell, Janus, Sakura Business Co., Gassnova, BEG at the University of Texas, University of Pennsylvania, IITB Mumbai, Fukada Geological Institute, Monea CCS Services and Global CCS Institute.

IEAGHG hope to be able to run their in-person International CCS Summer School in July 2021, in Bandung, Indonesia (to be hosted by ITB). This will be the 14th Summer School in the series after the postponement of the event in 2020 due to the COVID-19 pandemic.



Students & Lecturers at the ITB-IEAGHG Virtual CCUS Course, November 2020

Students have already been selected for this School but if you are a student interested in a future IEAGHG Summer School, please visit the website at https://ieaghg.org/summer-school.

2020-01 Monitoring and Modelling of CO_2 Storage,

report managed by Samantha Neades

The intention of this work was to develop an understanding of where future research efforts in CO_2 storage technologies should be focused on in the next decade, informing the potential directions for future research in order to fully maximise the potential benefits of storage technologies to commercial-scale CCS projects.

The study selects the most effective monitoring techniques in terms of cost-benefit and technical effectiveness, evaluates the impact of the technologies and recommends priorities for the future. End users intended for the report include operators of CCS projects, technology vendors, regulators, financial supporters, technical consultants, oil and gas operators, and the research community.

The following key messages came from the study:

- Monitoring technologies in CO_2 storage provide options to address site-specific risks which may affect project performance, storage security, human health, the environment and surface features.
- Monitoring provides accountability for injected CO_2, ensures regulatory requirements are met, provides detection of leakages and assesses CO_2 migration; key criteria in a risk assessment plan.
- There are opportunities to reduce costs in monitoring, and projects may benefit from doing such analyses when planning their monitoring programmes
- There is a confidence in the range of monitoring technologies available for large-scale CO_2 storage (on the scale of ~1 Mt CO_2 per year).
- There is a large range in monitoring costs, therefore it can be hard to interpret the cost-benefit ratio.
- Commercial scale projects storing on the order of 1 Mt CO_2/year usually incur costs on monitoring alone of around US $1-4 million (per year).
- Economies of scale do exist; so the higher the volume of CO_2 to be stored, the costs per tonne do decrease.
- Monitoring costs in construction, well drilling, characterisation, administrative and technical support are fairly consistent. Monitoring costs are generally a small fraction of the whole project (less than 5% of the total costs which is significant in comparison to capital and operating costs of capture facilities), and many monitoring methods are reasonably priced.
- Pilot projects focussed on research had high costs to validate a range of technologies.
- Earlier pilot projects (i.e. those that became operational in the 1990's and early 2000's) were not subject to the same regulations as new projects, meaning simpler monitoring programmes were undertaken and therefore costs were lower.
- Analogues for CO_2 storage (such as natural CO_2 fields, offshore oil and gas operations and natural gas storage) provide monitoring examples for the evaluation of long-term monitoring.
- There is an overall confidence in the range of technologies for monitoring CO_2 storage and current operational projects have made their monitoring programmes more efficient, focussing on the most useful methods to address specific project risks and better control costs.
- The path forward for implementing the safe storage of carbon dioxide seems stable.

2020-02 IEAGHG Monitoring & Environmental Research Combined Networks Meeting

report managed by Samantha Neades

The 13th meeting of IEAGHG's Monitoring Network was this year combined with the Environmental Research Network, to facilitate wider topic broaching and encourage broader discussions. This combined networks meeting was held from 20th –22nd August 2019 at the University of Calgary, Canada.

The two day meeting was preceded by a field trip to the Containment and Monitoring Institute (CaMI) field research station site visit. It was followed by a one day workshop on faults and their significance for CO_2 storage (report number 2020-03).

The meeting was designed to cover the following themes: developments in sensing ; lessons from managing field projects; uncertainty in quantification; monitoring for EOR compared with deep saline formations; fall-back plans; new case studies with real data; environmental impacts of monitoring and stakeholder engagement; up-well leakage; and monitoring postinjection for closure.

Of particular note were the first results from the STEMM-CCS project's controlled release experiment in the North Sea. This showed that a range of monitoring techniques were able to detect the small-scale release of CO_2, including small rapid changes in pH, and were able to quantify the amounts of CO_2 reaching the water column. This ability to now potentially quantify CO_2 seepage offshore was an impressive achievement recognised by the meeting. This experiment again showed that only a small percentage of the CO_2 escapes the sediment to the water column, much of it is caught by dissolution within the sediment, an important characteristic for seepage scenario planning.

Two group exercises were undertaken, many thanks to Sue Hovorka. One was to consider fall-back plans in the event of unexpected challenges in operational situations, and one to consider long-term post-injection monitoring. Both proved stimulating and thought-provoking for participants. Also in terms of post-injection monitoring, the Shenhua project in China was interesting to see the requirements there. The Tomakomai project, on the Japanese island of Hokkaido, again provided useful experiences in relation to project- and stakeholder-management in the event of natural earthquakes which they have experienced.

As usual at IEAGHG Network meetings, key conclusions and messages were drawn, and recommendations were made. One message was an appreciation of the need for sites such as the CMC Research Institute's Field Research Station (visited during the meeting) to allow R&D and testing of new monitoring techniques on a real CO_2 injection within the freedom of a research environment. The concluding high-level messages noted the great developments in marine and terrestrial sensing, particularly with quantification. Also the participants recognised the challenges arising from some regulations on requiring prescriptive long-term post-injection monitoring, which, however, should be risk-based and achievable with reliable tools, and noting that the objectives may be quite limited.

2020-03 IEAGHG Faults and their Significance for Large-Scale CO_2 Storage Workshop
report managed by Samantha Neades

The success of CO_2 Capture and Storage (CCS) technology depends on the safe, secure and long-term storage of CO_2 at large-scale (mega tonnes per site).

Upward migration and leakage of injected CO_2 along faults is a key risk. The aim of the workshop was to gain a greater understanding on how faults could influence long-term storage of CO_2. The workshop built on oil and gas industry experiences, as well as the research community, to gain a clear perspective on fault properties that are important to CO_2 storage. The 1-day event provided an opportunity to review laboratory experiments, field studies, and modelling results, to gain insights on the importance of faults for CO_2 storage. Current practices to evaluate fault seal as well as critical technical gaps were discussed.

The workshop gave an opportunity to review current research on CO_2 controlled release experiments and what could be learned from them, plus the contribution from simulations. The 1-day event documented critical issues for CO_2 storage related to faults, the experience of current experimental work, and identify remaining gaps in knowledge.

2020-04 The Clean Refinery and the Role of Electricity Generation
report managed by James Craig

The primary aim of this study was to explore the role of the 'clean refinery' concept and how it could contribute to the Paris Agreement's long-term objective to curb peak global greenhouse gas emissions.

Various options for refineries are available depending, not only on the complexity and degree of integration, but also on whether a refinery already exists or is still at the planning stage. In addition to these general considerations, the regional location, crude mix and local markets for refined products and electricity all influence the design, complexity and economic viability of 'clean refineries'.

Key messages

- The results of this study show that, in each of the three countries that were analyzed in this study (India, Nigeria and Brazil), the most favourable refinery configuration is one based on the conversion of opportunity crudes (high sulphur and extra-heavy crude oils), to the highest added-value distillate products.
- Refineries that produce higher value products, and environmental standards including CO_2 capture, will require policies that compensate for the extra costs of these measures.
- The economic analysis conducted as part of this study shows that the price of CO_2 needed to match the same Investment Rate of Return (IRR) of equivalent configurations without incorporated CO_2 capture would need to reach between US$32 – US$79 / ton of CO_2, depending on the refinery configuration.
- On-site electricity generation with CO_2 capture facilities can form part of the product portfolio, for export to local grids, from a Clean Refinery as an alternative to less refined and less desirable products. For example, in Brazil, fuel oil cannot be produced that meets the country's market-specification because of the very high viscosity of local crudes.

- As a common trend, and as expected, the yield in valuable distillates (LPG, gasoline, jet fuel and diesel) is directly proportional to the complexity of the configuration and relevant Nelson Index (which is a metric that allows comparison of the secondary conversion capacity of a refinery with its primary distillation capacity). Differences between the yields in the three countries are due to the very different nature of the processed crude oils.
- On the basis of the economic analysis of the refinery configurations developed in this study only two large-complex Indian refineries have a positive payback in less than 10 years. The other configurations have very unpromising paybacks of 16 – 20 years in three cases and indeterminate in the case of all three Brazilian cases and one Nigerian case (i.e. all four cases have negative Net Present Values (NPVs)). The Brazilian cases are penalized by the assumed crude cost in relation to the local product prices that are governed by market conditions and the relatively high Total Investment Cost (TIC).
- In a mature market, like the refining one, the key-drivers that still make a new refinery a profitable investment are: access to infrastructures; secure crude supply; medium-to-large capacity; and complexity.
- The economic analysis conducted as part of this study shows that the additional cost of CO_2 capture results in a loss of profitability if the value and environmental benefit of captured CO_2 is not credited.

2020-05 Value of Emerging and Enabling Technologies in Reducing Costs, Risks and Timescales for CCS report managed by Samantha Neades

The primary aim of this study is to evaluate the value of emerging and enabling technologies in reducing costs, risks and timescales for CCS from capture to storage.

This study was a horizon scanning exercise that aimed to understand the relevance of digital and enabling technologies for CCS and assess what benefits these technologies could offer to the large-scale deployment of CCS. Current R&D into the reduction of costs, risks, timescales and challenges in CCS primarily focusses on conventional improvement methods; emerging and enabling technologies have the potential to offer more opportunities for cost and risk reduction.

The study identified six main groups of emerging technologies that could benefit CCS:

1. Robotics, drones and autonomous systems
2. Novel sensors
3. Digital innovations
4. Virtual / augmented reality
5. Additive manufacturing
6. Advanced materials

The benefits in terms of costs are expected to be realised gradually; little cost savings would be available to projects beginning operation by 2025 but greater savings accessible from 2030 to 2040, reflecting both the current maturity level of the emerging technologies and the development timescales of CCS projects. A large proportion of CCS costs are capex costs, however the majority of applications with emerging technologies affect opex costs meaning that only modest savings in base project costs are projected. More significant cost reductions are across the chain and were projected to be in components associated with facility downtime and supply chain losses of CO_2. The greatest absolute savings are predicted to be in capture, and the greatest relative savings expected in storage sites.

Some of the key messages from the study include:

- There are a wide range of relevant applications for digital and enabling technologies in CCS that could potentially reduce costs and address risks and challenges in deployment.
- Although only some applications are currently under development in CCS, the benefits of these technologies discussed in the report are largely transferable from related sectors.
- Applications of artificial intelligence (AI) and the internet of things (IoT) in predictive maintenance and automation deliver the greatest potential reductions in project costs.
- Significant savings are only expected to be realised from 2030.
- The greatest absolute savings (in terms of $ /tonne of CO_2) are predicted to be in capture, whereas the greatest relative savings (in terms of percentage) are in storage.
- Globally, cumulative investment savings of almost $200billion in the lifetime costs of CCS projects deployed through to 2040 are possible.
- Cost model projections predict that:
    - o For sites operating in 2025, overall reductions of 2% in lifetime costs can be expected for onshore and offshore sites, resulting from 8-9% less OPEX (operational expenditure) costs and a reduction of 10% in supply chain losses,
    - o By 2040, 19% overall cost reductions are projected in offshore projects and 26% in onshore; a result of a 7-9% CAPEX (capital expenditure) reduction, 50% OPEX reduction and 50% reduction in injection facility downtime.

2020-06 CCS on Waste to Energy,
report managed by Monica Garcia

The rapid industrialization and economic growth have resulted in a significant increase of energy demand, population growth, and waste production, which represents a global challenge.

The World Bank estimated that 1.76 billion tons of CO_2 were generated from solid waste treatment and disposal in 2016, representing 5% of the total global CO_2 emissions. Municipal solid waste (MSW) can be processed through thermal or biological treatment. Incineration of waste, a kind of thermal treatment, emits chemicals. Landfilling, a type of biological treatment, may degrade valuable land resources and emit methane, a greenhouse gas even stronger than carbon dioxide.

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. As a result, the number of WtE plants has increased during the last decade. Large-scale WtE plants have been implemented in developed countries such as Japan, Germany, Sweden, the Netherlands, Denmark, and the United Kingdom. Moreover, advanced WtE technologies is an emerging area in renewable energy production, which can create valuable opportunities for reducing greenhouse gas emissions.

The implementation of carbon capture and storage (CCS) or utilisation (CCU) in WtE plants was not explored yet by IEAGHG. The objective of this study was to understand some of issues pertaining to this CCS/CCU opportunity and assess the potential of CCS/CCU in the WtE sector in different regions.

2020-07 Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture, report managed by Keith Burnard

The CCS has long been recognised as a key component of an effective mitigation strategy to decarbonise the power and industrial sectors. Commercial deployment of the technology, however, has been slow and must accelerate if it is to achieve its potential and contribute effectively to mitigating climate change. Accordingly, much effort has been focused on improving its techno-economic performance, not least the performance of fossil-fired power plants with CO_2 capture.

In this study, the techno-economic impacts of recent developments and improvements made to core components and system designs for both ultra-supercritical pulverised coal (USC PC) and natural gas combined cycle (NGCC) power plants with CO_2 capture were examined. Techno-economic benchmarks were updated and, in line with latest findings, the impact of markedly increasing the capture rates to achieve near-zero CO_2 emissions was investigated. Post combustion capture based on solvent scrubbing, currently the commercially leading option for capture on both pulverised coal and natural gas-fired power plants, was the technology of choice. The study also looked at improvements to the flexible operation of plants, the impact of efficiency improvements in USC PC and NGCC power plants, and the benefits of flue (or exhaust) gas recirculation in natural gas-fired plants.

Most previous techno-economic studies, including those commissioned by IEAGHG, have capped the CO_2 capture rate at 90%. However, a recent IEAGHG study has established that the 90% cap in capture rate ubiquitously adopted by most in the energy community is, in fact, an artificial cap. There are no technology barriers to prevent operation at capture rates consistent with net zero CO_2 emissions. This is important because, in the longer term, residual emissions from a 90% capture rate will not be compatible with the level of reductions needed to achieve the aims of the Paris Agreement. This is because, in a net-zero world, the residual emissions will also have to be mitigated.

It is essential that the broader energy and financial communities understand this potential in an environment where yet more stringent demands will be made on technologies to meet the challenge of climate change. Findings from this study show that, for both NGCC and USC PC plants, increasing the CO_2 recovery from 90% to much higher capture rates yields but modest increases in both LCOE and CAC. Reducing CO_2 emissions by a factor of 10 or thereabouts increases the LCOEs, relative to the 90% cases by just 5% (NGCC) and 8% (USC PC), and the CACs by 5% (NGCC) and 4.3% (USC PC). While these results are very promising, it is now important that these findings are tested in practice, i.e. in CCS plants at scale.

Further findings from the study show, for example, that flue gas recirculation leads to substantial savings in the CAPEX and OPEX of the capture unit, revealing it to be an effective option to reduce costs associated with CO_2 capture.

2020-08 Future role of CCS technologies in the power sector, report managed by Keith Burnard

For this study, a techno-economic analysis was undertaken to establish the likely roles of CCS technologies in the power sectors of four regions; Australia, China, the UK and the United States. The viability of BECCS, gas CCS and hydrogen to cost-effectively decarbonise baseload, mid-merit and peaking generation, respectively, in distinct power markets was demonstrated.

To decarbonise in coal-dependent regions, a progressive transition from coal power plants to BECCS was identified as a potentially attractive approach. The modelling also suggested that increasing CO_2 capture rates markedly above 90%, making plants effectively carbon-neutral, could be cost-effective at high load factors.

Realising the potential of CCS technologies in practice, however, will require policy incentives and regulatory actions to be put in place urgently to overcome the two main barriers to deployment – high capital expenditure and lack of revenue generation.

Economic constraints lie at the forefront of CCS-related risks and challenges. Projects usually involve high upfront capital investment (CAPEX) and, as captured CO_2 is not highly valued, they also lack mechanisms to recover operational expenditure (OPEX). Some of the major emerging support mechanisms or actions to address the market failure that stems from high CAPEX and OPEX, to create more investable business models for CCS, are spelled out in the report.

Incentives were also considered for CO_2 transportation and storage (T&S) business models. In the future, most CCS projects are likely to use shared T&S infrastructure, probably managed by dedicated companies. Clustering capture facilities, oversizing initial assets and utilising existing assets that would otherwise be decommissioned would significantly reduce the cost of T&S deployment. Furthermore, countries could accelerate T&S infrastructure roll-out via public ownership or regulated models which are currently applied to monopoly utilities in some regions.

This study shows that CCS technologies have different roles, from baseload to peaking operation, in diverse power markets. To determine what actions best suit its power market and unique circumstances, each country may want to expand on existing policy mechanisms that are proven to work well or to improve upon the existing frameworks. In addition to country-specific messages, mechanisms applicable across the regions are also addressed in the report.

2020-09 Understanding the cost of reducing water usage

report managed by Monica Garcia

Energy and water consumption are closely connected. The Energy-Water nexus defines the relationship between energy and water to ensure the availability of both resources.

Energy production consumes significant amounts of water; and equally, providing water demands energy. Power generation can impact water resources and increased electricity demand is projected in the coming years. In this scenario, the installation of carbon capture technologies in locations where the availability of water is limited must be studied, particularly in regions already suffering from water stress.

IEAGHG identified the need of a comprehensive techno-economic assessment of the Energy-Water-CCS nexus. This study was conducted in two phases. Phase 1 developed a hypothetical base case scenario of power plants with and without a PCC system in The Netherlands, assuming both on and offshore storage, and with and without treatment of the water extracted from the storage site for its reuse in the power plant. Phase 2 was based on four hypothetical PCC systems in South Africa, Australia, China and India.

2020-10 The Status and Challenges of CO_2 Shipping Infrastructures

report managed by James Craig

One of the challenges that faces CCS is how to transport significant volumes of compressed CO_2 from point sources to sites established for large-scale storage, especially offshore. Pipelines are one solution, but their viability depends on the volume to be transported and if the CO_2 comes from a variety of dispersed sources.The other option is to use dedicated sea tankers that can deliver CO_2 from one or more ports, either directly to an offshore storage site, or an intermediate shore-based facility connected via pipeline to the storage site.

IEAGHG commissioned a study with Element Energy, in collaboration with SINTEF Industry, Brevik Engineering and IOM Law. The objective of the study was to investigate and compare the technical and economic options of CO_2 transported by sea tankers and pipelines. Ship transport offers flexibility but weather conditions can constrain the operational windows and therefore the amount of CO_2 that can be delivered and stored. Two scenarios reviewed CO_2 shipped to an intermediate shore based facility before transmission via pipeline to an offshore storage site. An alternative option investigated direct delivery of CO_2 to an offshore storage site but without any holding time. Another option looked at direct delivery by a tanker to an offshore storage site with a temporary storage facility. This scenario would allow greater operational flexibility as it would enable CO_2 to be stored without reliance on a docked tanker.

The study also looked at the cost of pipeline transport depending on the quantity of CO_2 supplied and the distance compared with CO_2 delivered by sea tanker. This study shows that the pipeline option is cheaper but only over shorter distances. A range of ship sizes, in terms of capacity, were reviewed to try and identify if economies of scale could be achieved. It also explored current international regulations that govern international CO_2 transport.

Of the four scenarios modelled, and based on a shipping distance of 1,000 km, there is little cost advantage from increasing the ship size above 10,000 tCO_2. Conversely, there is also little penalty in cost by using larger ships. However, the optimum ship size will be highly dependent on the flow rate. Ideally, size and capacity could be customised for each specific logistics chain.

2020-11 Beyond LCOE: Value of technologies in different generation and grid scenarios, report managed by Keith Burnard

Since its introduction, the levelised cost of electricity (LCOE) has become ubiquitous in the evaluation and comparison of power generation technologies. While it is a readily accessible metric, it focuses exclusively on the cost of electricity produced from a given asset, or set of assets, and neglects to address the provision of ancillary services that are vital for the reliable operation of an electricity grid. This simplification was entirely appropriate for the electricity system of the 20th century, dominated at it was by fossil fuels and nuclear technologies, but it falls well short as a metric to compare technologies in a system to provide net-zero emissions by the mid-21st century.

This study aims to explore the potential for an alternative concept to LCOE that balances completeness and ease of use. The successful concept should offer a transparent, intuitive and comprehensive approach with which to compare the evolving impact of technologies within an electricity system – rather than simply providing direct technology-technology comparison. Various concepts have been proposed as alternatives to LCOE and, while many of them are excellent, no one method has emerged as a clear preference to LCOE; they variously suffer from computational complexity, large data requirements or lack of transparency.

Of all the services that each technology provides to the system, modelling undertaken for this study indicated that the provision of firm capacity (MW) and energy (MWh) services were the most crucial. An existing concept that assesses the capacity and the energy services of different technologies is the screening curve. However, while this concept represents a well-established method to compare thermal generation technologies, in its current form it is not suitable for the evaluation of intermittent renewables and storage technologies.

However, it is shown that this limitation can be overcome by incorporating the effective capacity factors of the technologies in the curve, which reflects the capacity and energy services provided by intermittent renewables. Storage technologies can also be incorporated in the approach by limiting their maximum hours of discharge to the curtailed hours of the electricity source (to represent the time the technology needs to charge) and to the maximum hours of operation (which corresponds to the time needed to charge and discharge). Applying these rules allows the screening curve approach to be used to evaluate the capacity and energy value of dispatchable and non-dispatchable power generation technologies, as well as energy storage technologies. This is an accessible approach to evaluate the impact of arbitrary levels of all power generation technologies on the total system cost. The proposed concept can also be used to estimate the level of economic deployment of technologies considered and to determine the optimal role the technologies can play.

This study proposes the modified screening curve concept as an alternative concept to LCOE, which shows that intermittent renewables have significant value by providing energy/fuel savings for the electricity system, with CCUS, as a low-carbon, dispatchable technology, having critical value by supplying capacity for security of supply.

2020-12 Review of constructability and operational challenges faced by CCUS projects, report managed by Monica Garcia

IEAGHG have explored in the past techno-economic information of large demonstration projects and individual projects built in specific locations were explored in detail. However, a deep analysis of the construction and operation aspects, together with the factors for the project success was needed.

IEAGHG identified the need to provide a guide on constructability and operation for new CCS users. The objective of this study was to collect information from CCS projects to support the decisions during the transition from the planning to the execution phase.

This study analysed a complete list of large CCUS projects from which relevant experience could be extracted. The projects were divided into three categories: operating projects; under construction or at advanced development; and cancelled projects. Moreover, a guide for new entrants was included, aiming to provide material to aid potential developers with the planning phase of large-scale CCS facilities to ensure successful construction, commissioning and operation.

From the analysis, it can be extracted that key factors for the success of CCS projects include early design, which should include the integration with the original facility, previous testing under the specific conditions, and involvement of stakeholders from the early stages of the project. The business case and coordination of the cross-chain (including capture, transport, and use/storage) are essential to maintain the operation of the CCS project throughout its operational life. Other aspects will include detailed planning based on a simulation of the common construction site management, plant commissioning, start-up, maintenance, shut-down and decommissioning.

The reasons for cancellation include: lack of long-term economic viability (including dependency on government subsidies and changes on funding schemes); uncertainty around risk management and allocation; not enough integration of the capture system with the original facility, or lack of planning in advance (including technical aspects not related to the CCUS system); and flawed design which impacts on the construction and operation.

2020-13 High Temperature Solid Looping Cycles Network Combined Meetings Report, report managed by Jasmin Kemper

The IEAGHG High Temperature Solid Looping Cycles Network (HTSLCN) emerged from the preceding International Workshop on In-situ CO_2 Removal (ISCR) and aims at bringing together researchers and developers of CO_2 capture technologies that operate at high temperatures in cyclic processes using either circulating or fixed beds of solids.

The 6th HTSLCN Meeting took place from 1st to 2nd September 2015 at the Department of Energy, Politecnico di Milano,in Italy. It was jointly organised by IEAGHG and Politecnico di Milano. 72 attendees from 19 countries enjoyed a two-day programme with 45 presentations, organised in 8 sessions, and site visits to research facilities at Politecnico di Milano.

The 7th HTSLCN Meeting took place from 4th to 5th September 2017 at Kulturens Hus in Luleå, Sweden, hosted by Swerea MEFOS. 50 attendees enjoyed a two-day programme with 39 presentations and participated in the Grand Opening of the STEPWISE pilot plant.

The 8th HTSLCN Meeting took place from 20th to 21st of January 2020 at Chemelot Industrial Park, in Geleen, The Netherlands, hosted by TNO in collaboration with the CLEANKER and LEILAC projects. 30 attendees enjoyed a two day programme with a total of 16 presentations and a site visit to the LEILAC plant in Lixhe, Belgium.

2020-14 Carbon Capture and Storage and the Sustainable Development Goals

report managed by Jasmin Kemper

A few months prior to the Paris Agreement, in September 2015 'Transforming our World: the 2030 Agenda for Sustainable Development' was adopted by the United Nations General Assembly.

This resolution, consisting of 17 SDGs, covering a wide range of human development areas and broader environmental sustainability issues, is a follow-up to the Millennium Development Goals. Both the Paris Agreement, and the 2030 Agenda, although negotiated under different multilateral processes, are considerably interlinked.

The Paris Agreement emphasises the need for sustainable development considerations in low-emissions transitions; at the same time combatting climate change is one of the 17 SDGs. The IPCC's Special Report on 1.5°C (SR1.5) has made an initial assessment on the synergies and trade-offs between mitigation options and sustainable development, including CCS use in the energy supply and industrial sectors. The IPCC assessment represents a useful first insight on the interaction of CCS with the SDGs.

For a number of SDGs no assessment was feasible as no relevant public literature could be identified. A dedicated, in-depth assessment, as was done in this study, can further help to support and complement the findings of the IPCC.

The 17 Sustainable Development Goals (SDGs)

2020-TR01 Agenda Workshop on Hydrogen Production with CCS, report managed by Monica Garcia

Hydrogen is a key raw material to other energy intensive industries. Globally, nearly 90% of the hydrogen produced industrially is consumed by the ammonia, methanol and oil refining industries. Moreover, hydrogen could soon play a significant role in the decarbonisation of power, space heating (i.e. industrial, commercial, building and residential heating) and transport fuel (i.e. use of fuel cell vehicles).

Although the steam methane reformer route (SMR) is the leading technology for H_2 production from natural gas or light hydrocarbons, there are other mature and emerging alternatives. Similarly, while increasing the process efficiency has shown a CO_2 emissions reduction of nearly 10%, CCS has been identified as a key strategy to cut down CO_2 emissions from hydrogen production.

Against this background the Carbon Sequestration Leadership Forum (CSLF) decided to map activities on hydrogen production with CCS in member states and elsewhere. One conclusion of that exercise was to hold a workshop with other organisations.

A steering committee was formed to organise this workshop, held on November 6th 2019, and hosted by EDF and Club CO2. Steering group members included representatives from CSLF (Lars Ingolf Eide), IEA-GHG TCP (Monica Garcia Ortega), IEA-Hydrogen TCP (Mary-Rose de Valladares), and Equinor (Christoph Schäfer). Prior to the workshop, the following objectives were delineated:

1. Define the Research, Development & Demonstration (RD&D) needs for decarbonised hydrogen
2. Identify the role that decarbonised hydrogen can play in a future low-carbon society
3. Provide recommendations on decarbonised hydrogen to policy-makers
4. Lay a foundation for further co-operation

This workshop was held for one day, devoted to a plenary session addressing three general topics, and including 90 attendees from 19 countries. Each session included several invited presentations, followed by a discussion among the workshop attendees.

2020-TR02 4th International Workshop on Offshore Geologic CO_2 Storage

report managed by Tim Dixon

The 4th International Workshop on Offshore Geologic CO_2 Storage was held 11-12 February 2020, hosted by the University of Bergen in conjunction with the EU-Funded STEMM-CCS project in Norway. The workshop addressed how to develop CCS projects with offshore storage and built on the recommendations and topics raised at the previous workshops.

The aim of the workshop series is to facilitate sharing of knowledge and experiences among those who are doing offshore CO_2 storage and those who are interested, and to facilitate international collaboration on projects.

Over 150 attendees from 18 countries participated in this 4th workshop. The agenda included sessions on infrastructure, project updates, emerging country needs and progress, deep subsurface monitoring and modelling (shallow monitoring was covered by the STEMM-CCS portion of the workshop), regulatory frameworks and brainstorming toward an international project. Each session included discussion, and the workshop concluded by agreeing overall conclusions and recommendations. There were also twenty poster presentations for the Offshore Workshop.

2020-TR03 IEAGHG Monitoring Network Virtual Discussion Panel Report

report managed by Samantha Neades

This discussion panel was held by webinar on Wednesday 12th August at 10pm BST, with the theme of engaging regulators, looking at 'Regulation, Industry and Research - Translating Monitoring Research to Meet Commercial Needs'.

The panellists comprised different CO_2 storage monitoring stakeholders; operators, regulators and researchers and attendees were asked to submit questions for the panellists to consider prior to the event, of which over 120 were received. 70 participants joined the event, in addition to the 8 panellists involved.

The aim of the panel was to discuss the translation of CO_2 geological storage monitoring research into regulations and commercial-scale projects. It began with a scene setting presentation and framing questions with in-depth and thoughtful discussion with operator, regulator and research representatives from the US, Australia, and Norway.

This discussion panel was an ideal opportunity for all stakeholders actively engaged in CO_2 geological storage projects and practical research in monitoring to share and learn about how the information from research and our Monitoring Networks can be used to meet commercial needs.

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 2020, 14 technical reports and 3 technical reviews were published (see page 20 for overviews or 34 for the list); three 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 33 blogs during 2020.

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 25 IPs in 2020.

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 2019 Annual Review....

2150 Followers (5.49 % increase)

facebook

1553 Likes (4.01% increase)

Linked in

1008 Group Members (19.14% 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
COP25 Climate Change Negotiations: Cooperative Approaches, Divided Nations COP25 is the longest in the history of the United Nations climate change negotiations. Article 6 "Cooperative Approaches" of the Paris Agreement divided nations. A mix of issues were decided but nations could not agree on others. Much of the focus and energy was invested in the negotiations of market-based and non-market based approaches outlined in Article 6. At the last moment, overtime, talks collapsed over how some holdover issues from the Kyoto Protocol should be decided. Technology transfer issues were agreed in this meeting. However, nations could not agree on the role and commitment of long term climate finance to developing nations, which will continue to be an important factor in the scale-up of climate actions, including technology development, transfer, and deployment.	14/01/20	35	75
Launching CO_2 DataShare – a digital portal for making CO_2 storage data available Sharing of reference datasets from pioneering CO_2 storage projects is essential to accelerate improved understanding, build capacity, reduce costs and minimize uncertainties associated with CO_2 storage in deep geological formations. The CO_2 Storage Data Consortium is an international network aiming to make such datasets available for research and development. To achieve this, the consortium-driven project "CO_2 Data Share" has built a web-based digital platform for CO_2 storage data exchange. The purpose is to make it easy to find, access and use well-documented CO_2 storage datasets relevant for addressing technology gaps and reducing uncertainty.	27/02/20	83	239
Understanding the cost of reducing water usage in coal and gas fired power plants with CCS In this webinar, Monica Garcia (IEAGHG), Regina Sander (CSIRO Energy), and Paul Feron (CSIRO Energy), discussed the motivation and results of the IEAGHG technical study "Understanding the cost of reducing water usage in coal and gas fired power plants with CCS", carried out by CSIRO.	25/06/20	66	232
Value of Emerging and Enabling Technologies in Reducing Costs, Risks & Timescales for CCS This webinar looked at the recent IEAGHG study on the Value of Emerging and Enabling Technologies in Reducing Costs, Risks & Timescales for CCS. This work was a horizon scanning exercise aiming to understand the relevance of digital and enabling technologies for CCS and assess what benefits these technologies could offer to the large-scale deployment of CCS.	08/09/20	78	213
Beyond LCOE: Value of technologies in different generation and grid scenarios Webinar Since its introduction, the levelised cost of electricity (LCOE) has become ubiquitous in the evaluation and comparison of power generation technologies. While it is a readily accessible metric, it focuses exclusively on the cost of electricity produced from an asset and neglects to address the provision of ancillary services that are vital for the reliable operation of an electricity grid. This simplification was entirely appropriate for the electricity system of the 20th century, dominated at it was by fossil fuels and nuclear technologies, but it falls well short as a metric to compare technologies in a system to provide net-zero emissions by the mid-21st century.This webinar looked at the various concepts that have been proposed as alternatives to LCOE and the potential for a concept that balances completeness and ease of use was explored.	15/12/20	73	137

Table 1: List of 2020 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
2020-01	Monitoring and Modelling of CO_2 Storage: The Potential for Improving the Cost-Benefit Ratio of Reducing Risk	20/02/2020
2020-02	IEAGHG Monitoring & Environmental Research Combined Networks Meeting	26/03/2020
2020-03	IEAGHG Faults and their Significance for Large-Scale CO_2 Storage Workshop	26/03/2020
2020-04	The Clean Refinery and the Role of Electricity Generation	01/05/2020
2020-05	Value of emerging and enabling technologies in reducing costs, risks and timescales for CCS	14/07/2020
2020-06	CCS on Waste to Energy	31/12/2020
2020-07	Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture	23/07/2020
2020-08	Future role of CCS technologies in the power sector	20/08/2020
2020-09	Understanding the cost of reducing water usage in coal and gas fired power plants with CCS	07/09/2020
2020-10	The Status and Challenges of CO_2 Shipping Infrastructures	28/07/2020
2020-11	Beyond LCOE: Value of technologies in different generation and grid scenarios	29/09/2020
2020-12	Review of Constructability and Operational Challenges faced by CCUS projects	09/09/2020
2020-13	IEAGHG High Temperature Solid Looping Cycles Network – Combined meeting report	16/10/2020
2020-14	CCS and the Sustainable Development Goals	15/12/2020

Table 2: List of 2020 Technical Reports

Review No.	Technical Review Title	Issue Date
2020-TR01	Agenda Workshop on Hydrogen Production with CCS	21/02/2020
2020-TR02	4th International Workshop on Offshore Geologic CO_2 Storage	30/04/2020
2020-TR03	IEAGHG Monitoring Network Virtual Discussion Panel	25/09/2020

Table 3: List of 2020 Technical Reviews

IP No.	Information Paper Title	Author	Issue Date
2020-IP01	EU-Wide Classification System ('Taxonomy') for Sustainable Investments	SN	28/01/2020
2020-IP02	The role and value of CCS in different national contexts	KB	31/01/2020
2020-IP03	CONFIDENTIAL	TD	07/02/2020
2020-IP04	Mission Innovation Report	MG	10/02/2018
2020-IP05	CCUS and Energy Intensive Industries (EIIs)	MG	19/02/2020
2020-IP06	The Hydrogen Economy Outlook released by BloombergNEF	MG	14/04/2020
2020-IP07	New paper on GHG life cycle emissions of a DAC + FTS process for synfuel production	JK	05/05/2020
2020-IP08	Global Energy Review 2020: The impacts of the Covid-19 crisis on global energy demand and CO_2 emissions	KB	11/05/2020
2020-IP09	CONFIDENTIAL	TD	11/05/2020
2020-IP10	ADB report on CCUS readiness	KB	16/07/2020
2020-IP11	DOE Report on Petra Nova	KB	02/09/2020
2020-IP12	Artificial Intelligence and CCS	SN	03/09/2020
2020-IP13	CCUS in the EU Recovery Plan	SN	04/09/2020
2020-IP14	Release of the IEA's Energy Technology Perspectives 2020	KB	15/09/2020
2020-IP15	IEA Press Webinar: Special Report on Carbon Capture Utilisation and Storage: CCUS in Clean Energy Transitions	KB	01/10/2020
2020-IP16	CONFIDENTIAL	JC	12/10/2020
2020-IP17	CONFIDENTIAL	JK	14/10/2020
2020-IP18	G20 Energy Ministerial Communique	SN	15/10/2020
2020-IP19	World Energy Outlook 2020	KB	03/11/2020
2020-IP20	CONFIDENTIAL	TD	03/11/2020
2020-IP21	Workshop on CO_2 Infrastructure and Industrial Clusters	JC	17/11/2020
2020-IP22	The Adopted Provisional Application of the London Protocol's CCS Export Amendment	TD	13/11/2020
2020-IP23	CCUS for low carbon strategies in industries workshop	MG	10/12/2020
2020-IP24	Lessons from Longship	KB	16/12/2020
2020-IP25	CONFIDENTIAL	TD	18/12/2020

Table 4: List of 2020 Information Papers

Staff Abbreviations:
JC: James Craig | JK: Jasmin Kemper | KB: Keith Burnard | MG: Mónica García
SN: Samantha Neades | TD: Tim Dixon

Blog Title	Author	Issue Date
COP25 and CCS	TD	10/01/2020
4th Offshore Workshop and visit to Northern Lights project	TD	17/02/2020
STEMM-CCS Open Science Meeting provides reassurance on offshore environmental monitoring	TD	17/02/2020
New IEAGHG Technical Report: 2020-01 'Monitoring and modelling of CO_2 storage: The potential for improving the cost-benefit ratio of reducing risk'	SN	18/02/2020
International Carbon Capture, Utilization and Storage Conference 2020 (iCCUS 2020) 25-26 February 2020, Riyadh	KB	28/02/2020
UK Government CCS funding pledge is a welcome boost	TB	11/03/2020
IEAGHG and COVID-19	TD	20/03/2020
New IEAGHG Reports: Monitoring & Environmental Research Combined Networks Meeting and Workshop on 'Faults and their significance for large-scale CO_2 storage'	SN	27/03/2020
GoMCarb Annual Meeting 2020	TD	30/03/2020
Kick-off meeting of the C4U project (Advanced Carbon Capture for steel industries integrated in CCUS Clusters)	MG	27/04/2020
Review of Aquistore Webinar presented on 12th May 2020	JC	15/05/2020
CCUS in the Asia Clean Energy Forum 2020	TD	19/06/2020
The CO_2 DataShare Digital Platform has Launched and is Open for International Research	JC	25/06/2020
IEA Special Report on Clean Energy Innovation	KB	03/07/2020
Summary of the IEA Clean Energy Transitions Summit	KB	13/07/2020
Value of Emerging and Enabling Technologies in Reducing Costs, Risks & Timescales for CCS	SN	14/07/2020
New IEAGHG report: Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture	KB	23/07/2020
New IEAGHG report: The Status and Challenges of CO_2 Shipping Infrastructures	JC	28/07/2020
New IEAGHG report: Global Future Role of Power CCS Technologies	KB	20/08/2020
IEAGHG Modelling and Risk Management Network Meeting includes an Keynote address on Class VI specifications from Lynn Helsm, of the North Dakota Industrial Commission	JC	28/06/2018

Staff Abbreviations:
JC: James Craig
JK: Jasmin Kemper
KB: Keith Burnard
MG: Mónica García
SN: Samantha Neades
TB: Tom Billcliff
TD: Tim Dixon

Table 5: List of 2020 Blogs

Blog Title	Author	Issue Date
US DOE-NETL's 2020 Integrated Project Review Meeting (Virtual)	JC	01/09/2020
New IEAGHG Report: Understanding the cost of reducing water usage in coal and gas fired power plants with CCS	MG	07/09/2020
New IEAGHG Report: Review of Constructability and Operational Challenges faced by CCUS Projects	MG	09/09/2020
News from US DOE-NETL's 2020 Carbon Storage Project Review Meeting (Virtual)	SN	16/09/2020
Key Financing Principles for CCUS – launch event by CEM CCUS Initiative	TD	16/09/2020
New IEAGHG report: Beyond LCOE: Value of technologies in different generation and grid scenarios	KB	29/09/2020
Japan-Asia CCUS Forum 2020	JC	08/10/2020
IEA Iron and Steel Technology Roadmap	MG	12/10/2020
The Clean Energy Ministerial and CCUS	SN	15/10/2020
US DOE NETL Carbon Capture Project Review Meeting	MG	02/11/2020
Public acceptance of CCUS technologies facing challenging crossroads	TB	30/11/2020
CCUS Virtual Course for Asia-Oceania Region	SN	01/12/2020
New IEAGHG report: CCS and the sustainable development goals (SDGs)	JK	15/12/2020

Staff Abbreviations:
JC: James Craig
JK: Jasmin Kemper
KB: Keith Burnard
MG: Mónica García
SN: Samantha Neades
TB: Tom Billcliff
TD: Tim Dixon

Table 5: List of 2020 Blogs (Continued)

IEAGHG Presentations Made in 2020

Date	Meeting Title	Presentation Title	Speaker
11/02/2020	STEMM-CCS Open Science Meeting and 4th International Workshop on Offshore Geologic CO_2 Storage, Bergen, Norway	Welcome	TD
11/02/2020	4th Offshore CCS Workshop, Bergen, Norway	Update on the London Protocol CO_2 Export Resolution	TD
11/02/2020	4th Offshore CCS Workshop, Bergen, Norway	Global Sum-up	TD
10-11/03/2020	Workshop on Representing Carbon Capture Utilization and Storage, College Park, Maryland, USA	IEAGHG perspective on CCUS	KB
23/04/2020	University of Derby	CCS Overview & IEAGHG Introduction	SN
25/06/2020	IEAGHG Webinar	Reducing Water Usage in Power Plants with CCS	MG
17/08/2020	USGS	An International Update on CCUS from IEAGHG	TD
19/08/2020	DOE-NETL 2020 Integrated Project Review Meeting	An International Update on CCUS from IEAGHG	TD
19/11/2020	LCRI Webinar Series	Techno-economic evaluation of blue hydrogen production and its integration in ammonia and methanol production	MG
03/12/2020	CCSA CCUS2020 Conference	One year to COP26	TD
10/12/2020	IEA Working Party on Fossil Energy 80th meeting	Update from GHG TCP (IEAGHG)	TD

Staff Abbreviations:
KB: Keith Burnard MG: Mónica García SN: Samantha Neades TD: Tim Dixon

Table 6: List of 2020 Presentations

Members of the Programme

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

AUSTRIA
Mr Theodor Zillner (M) | Mr Ernst Goettlicher (A)

CANADA
Dr Eddy Chui (M)

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

FINLAND
Aila Maijanen(M) | Elke Schnabel(A)
Elina Maki (A)

FRANCE
Mr Michel Giora (M) | Isabelle Czernichowski(A)

INDIA
Dr Atul Kumar (M)

JAPAN
Mr Ryozo Tanaka (M) | Dr. Ziqui Xue (A)
Hiroto Yoshikawa (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
Mr Moufid Benmerabet (M) | Dr Mohammed Ali Zarie Zare (M)
Dr Eleni Kaditi (A)

SOUTH AFRICA
Dr Anthony Surridge (M) | Mr Thulani Maupa (A)

SWEDEN

Svante Soderholm (M) | Benny Fillman (A)

SWITZERLAND

Dr Sophie Wenger (M) | Marine Pérus(A)

UNITED KINGDOM

Mr Matthew Taylor (M) | Mr Will Lochhead (A)

USA

Jarad Daniels (M) | John Litynski (A)

Mr Mark Ackiewicz (M & VC) | Anhar Karimjee (A)

Baker Hughes

Mr Paul Doucette (M) | Ms Allyson Anderson Book (A)

Chevron

Mr Arthur Lee (M)

CIAB

Mr Peter Morris (M) | Mr Mick Buffier (A)

Karl Bindemann (A)

Doosan Babcock

Jeanette Friery (M) | Jonathan SlaterA)

EPRI

Mr Robert Trautz (M)

equinor

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

ExxonMobil

Mr Ganesh Dasari (M)

INSTITUTO NACIONAL DE ELECTRICIDAD Y ENERGÍAS LIMPIAS

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

Bandung Institute of Technology

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

JGC

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

J-POWER

Seiji Hongo (M) Shinichi Sakuno (A)

JÜLICH FORSCHUNGSZENTRUM

Eric Busche (M)

جامعة خليفة
Khalifa University

Mohammad Abu Zahra (M)

BR PETROBRAS

Miss Ana Paula Musse (M)

RWE The energy to lead

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

SHELL

Dr Owain Tucker (M)

Southern Company

Richard Esposito (M)

TOTAL

Stanislas Vanderberg (M) Philip Llewellyn (A)

iea

Samantha McCulloch

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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