Evaluating technology options to mitigate greenhouse gas emissions

annualreview 2019

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

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

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

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Inside Cover Image: KCC Bench Plant, Akashi, Japan, site visit at PCCC-5

Front and Back Cover Images: Abu Dhabi skyline - location for GHGT-15; Architecture in Japan, location of PCCC-5; seismic monitoring at CaMI facility, Canada; the CaMI facility, Canada; delegate packs at PCCC-5, Kyoto, Japan.

Contents

Attendees at PCCC-5, Kyoto / Delegates at the Fault Workshop Meeting, University of Calgary, Canada

Chairman's Message

Messages on the impact of climate change are getting stronger and more direct.

Wildfires across 3 states in my own sub continent, Australia, have emitted 250Mt CO_2 since August 2019 – equivalent to almost half of Australia's annual greenhouse gas emissions. Experts say the pulse of CO_2 from this season's bushfires is significant, because even under normal conditions it could take decades for forest regrowth to reabsorb the emissions. Added to this, a spate of huge fires in northern Russia, Alaska, Greenland and Canada have discharged over 160Mt CO_2 between June and August 2019, far exceeding the previous record for the Arctic.

In July 2019 the fever on our planet was the hottest on record. According to new data from the World Meteorological Organization, it broke the record for the hottest month since analysis began. This followed on the heels of the warmest June on record. July 2019 was around 1.2°C warmer than pre-industrial times and temperature records were shattered from New Delhi to Anchorage, from Paris to Santiago and from Adelaide to the Arctic Circle.

The events noted above this year have been accompanied by 2 studies released by the Intergovernmental Panel on Climate Change (IPCC). The IPCC Special Report on Climate Change and Land was released in August 2019, which noted that we must dramatically change the way we use land to limit global warming to safe levels by 2030. The report concludes that *'Climate Change is already impacting people and ecosystems on land also, whist climate change is causing major changes to land, changes to land are also causing climate change'.* The IPCC Special Report on The Oceans and Cryosphere in a Changing Climate was released a month later in September and revealed the serious impacts of sea-level rise, warming waters, and ocean acidification. The report also highlighted the benefits of ambitious mitigation and effective adaptation for sustainable development and, conversely, the escalating costs and risks of delayed action.

Kelly Thambimuthu speaking at GHGT-14

Hard on the heels of these scientific assessments by the IPCC, the UNEP Emissions Gap Report for 2019 provides the first-ever estimate of annual cuts needed to stay on track with the 2015 Paris Agreement, and emphasizes that the levels of ambition in the Nationally Determined Contributions (NDC) must increase at least fivefold for the 1.5°C goal and threefold for the 2°C goal. Indeed the emissions reduction challenge for greenhouse gases is very clear and requires more concerted action collectively on multiple fronts covering energy use, agriculture and life style changes as alluded in last year's IPCC Special Report on Global Warming of 1.5C. Supported by the messaging in this 2018 IPCC special report, carbon dioxide reduction technologies including CCUS and CCUS with bioenergy (BECCS) have a significant role to play in achieving our goals to protect this planet.

Indeed, the messages and evidence of the impact of climate change are very clear and its time to activate our collective resolve and will to act decisively.

K. V. Thambimuthu.

Kelly Thambimuthu,
Chairman of the IEAGHG Executive Committee

General Manager's Summary

2019 was a year of changes, successes and challenges. The major change for me was stepping into the very large shoes of John Gale when I took over as General Manager in mid-year. I thank John very much for creating a great organisation and legacy.

IEAGHG activities continued apace in 2019, driven by our great team of enthusiastic and capable staff. We were very pleased with our reports, a successful PCCC-5 conference in Kyoto, our Monitoring Network and Environmental Network meeting in Calgary, and a new workshop on faults. With the Summer School hosted by the International CCS Knowledge Centre, our alumni reached 626, and we see more alumni in positions of authority and decision-making.

Of all of IEAGHG reports in recent years, possibly the most strategically important for CCS is the report to show that higher capture rates are feasible (up to 99.7%) and at modest extra cost. This realisation should change how CCS is further represented in energy and climate modelling to the end of the century, giving it an even greater role to play.

A major success was the London Protocol agreeing to allow export of CO_2 over international borders for offshore storage. This was an issue close to my heart, as I had been deeply involved in the original amendments to allow offshore storage in 2006, and the export of CO_2 was the one issue left unresolved, and becoming a significant legal barrier for CCS deployment where offshore storage is involved. Thank you to Norway for leading on the resolution to this. IEAGHG was pleased to be able to play a supporting role within the negotiations.

In terms of challenges, COP25 changed host country at short notice (well done to UNFCCC and to Spain for managing this) and it delivered less than hoped for from the negotiations. However we were again involved in the only UNFCCC Side-event on CCS, a key source of information on CCS in the COP which was again a success, so many thanks to our collaborators the University of Texas, CCSA, the International CCS Knowledge Centre, and Bellona.

I'm sorry to say that we had the sudden illness of one of our core staff members, our Communications Manager Becky Kemp, and we wish her well in her recovery.

And as we now know, a new immense challenge to face us all was about to arise in early 2020, COVID-19, impacting the planning of many of IEAGHG's forthcoming activities.

And all the time through 2019, climate change continued to increase and its impacts were felt more and more, and the world needed more CCUS than was being delivered. Faced with these challenges, my suggestion is "Keep Calm and Capture On" (borrowed from an engineer at SaskPower).

Tim Dixon,
General Manager, IEAGHG

Key IEAGHG Achievements in 2019

Conference
PCCC-5
112 Delegates

Meetings
CCS Cost Network
50 Delegates

13th IEAGHG Summer School
39 Students

12th Monitoring Network Meeting
70 attendees

Fault Workshop
55 Delegates

Published to Online Media

External Presentations by IEAGHG Staff

3 Webinars
433 YouTube views

9 Technical Reports
3 Technical Reviews
15 Information Papers
4 Briefing Papers

Page Views:
28,971

Views of IEAGHG Website:
14,122 Sessions

IEAGHG Operations Report

As a member of the IEA's Energy Technology Network (ETN) we operate on a 5 year term, and 2019 was the second year of our current five year operating term.

Membership increased in 2019 by three members. Welcome to The Netherlands, Sotacarbo, and ITB. With 36 members in total giving us an annual income of £1.56m. The budget was spent as illustrated in the graph (right).

The Executive Committee that is comprised of our member representatives, which acts as the Governing Body overseeing IEAGHG's activities, met twice in the year. The first meeting was held in May 2019 in Helsinki, Finland hosted by VTT. As well as the normal business of assessing IEAGHG's activities and agreeing new ones, the meeting also afforded members to visit the Neste's Porvoo refinery.

The second Executive Committee meeting was held in October 2019, in Houston Texas, hosted by Exxon. As well as the normal business of assessing IEAGHG's activities and agreeing new ones, the meeting also afforded members a visit to the NET Power facility and the Petra Nova CCS project.

Attendees gather at Petra Nova CCS Project, Texas, October 2019. Image courtesy of Exxon Mobil.

Delegates at the Fault Workshop meeting, University of Calgary, Canada

Attendees at the CCS Cost Network 2019 Workshop, Palo Alto, California, USA

5th Post Combustion Capture Conference

It was with very high enthusiasm that we delivered the 5th Post-Combustion-Capture-Conference (PCCC5). It took place in Kyoto (Japan), from the 17th to the 20th of September 2019, including two site visits to Kawasaki (KHI) and Nanko Power station.

PCCC-5 was a great opportunity to interact with many of the leading, international stakeholders in carbon capture and to share experiences on emerging technologies, demonstration projects and policies. Around 140 attendees from more than 20 countries participated. Keynote speeches were given by high-level representatives from Australia, China, Japan and the United States. Compared with earlier PCC Conferences there was high participation from industry and, given deployment is still off-track for CCS to meet its climate goals, this was particularly encouraging.

There were sessions at PCCC-5 on a range of important topics that included process configurations, separation technologies, applications, modelling, cost assessments, environmental assessments and demonstration activities. Significantly, current and past IEAGHG studies played into many of the discussions. In the session on cost assessments, for example, results from IEAGHG-related activities underpinned two of the five presentations given, with one based on a collaborative venture with several organisations promoting the transparency of cost assessments on CCUS studies and the other based on an IEAGHG study that explored emerging capture technologies and their potential to reduce costs.

Engagement with industry was especially notable in the sessions on environmental assessments and applications, where we were privileged to hear, e.g. from MHI Engineering, Toshiba and KEPCO describing their large-scale testing programmes.

The key messages from PCCC-5 are:

- Major advances in post-combustion capture continue to be made. With innovative systems, it is important to continue investigating, to bring new solutions to the market while testing mature systems at large scale under different conditions

and for different applications. Transparency is key; without transparency, without sharing results both positive and negative, progress will suffer.

- While new components and new solvents are necessary, novel process integration and new configurations are equally important. The implementation of advanced configurations, for example, has led to significant reductions in energy consumption.
- Deployment is essential – at all scales, but particularly at commercial scale. In this regard, the keynotes from Lynn Brickett (US-DOE) and Takashi Honjo (RITE) were particularly meaningful. Although deployment is slowly increasing, helped by some supportive policies, the trend must accelerate.
- As illustrated by many speakers at PCCC-5, collaboration is key to positive progress. This was exemplified in the messages from Kazuo Fueta (METI) and Frank Norton (NCCC). Sharing experiences is essential to transfer learnings and, ultimately, for faster deployment.
- Carbon capture is an essential technology in the portfolio to decarbonise the power, industry and transport sectors. The technology has been demonstrated at scale to be technically feasible in both power and industry sectors. Of the systems for capturing CO_2 from these sectors, post-combustion capture is the most advanced. However, greater effort is still needed. While awareness is growing, many of the initiatives presented and the relationships developed at PCCC-5 will play an influential role in the future of CCUS.

More information on the PCCC series can be found on the IEAGHG website: www.ieaghg.org

Nanko Pilot Plant, Osaka, Japan.

Looking to 2021: GHGT-15 in Abu Dhabi

The GHGT conference will visit the Middle East for the first time in 2021. Hosted by Khalifa University, Abu Dhabi, GHGT-15 will take place in March 2021.

The GHGT-14 conference proceedings were published in 2019, with 719 papers hosted on the SSRN platform - conference proceedings and 72 papers accepted for the peer reviewed Special Issue GHGT-14 proceedings in the International Journal of Greenhouse Gas Control. Downloads from both publishing platforms now exceeds 11,000, showing the value of the papers published within the CCUS industry.

Following the success of GHGT-14, the next conference in the series was subsequently awarded to our UAE member – Khalifa University who are based in Abu Dhabi, and it will be the first time a GHGT Conference has visited the Middle East region. The GHGT-15 Abu Dhabi was announced via the newly launched and redesigned website www.ghgt.info in May 2019, with the call for abstracts opening in September 2019.

Following the outbreak of the COVID-19 pandemic, the GHGT-15 Steering Committee took the decision to postpone the conference from October 2020, so it will now take place on **15-18 March 2021**.

The GHGT conference series has established itself as the principal international conference on greenhouse gas mitigation technologies especially on CCS and we are looking forward to another successful conference hosted by our colleagues from Khalifa University in Abu Dhabi.

For more information, please visit www.ghgt.info

Aerial view of Abu Dhabi, United Arab Emirates, location for GHGT-15

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.

UNFCCC COP25

COP25 was held in Madrid, with impressive reorganisation by the UNFCCC secretariat and Spanish hosts to relocate it from Chile at just a few weeks' notice. A main ambition of this COP was agreement on international cooperative mitigation actions, including emissions trading, known as Article 6 of the Paris Agreement. This was the one area of the Paris Agreement rulebook left unfinished at COP24. Much attention was also being given to the two new IPCC reports on Oceans and Cryosphere and on Land, and the ongoing IPCC AR6 process, noting the opportunities for input of IEAGHG key reports such as on Higher Capture rates (2019-02).

Article 6 is very important as it would create the means, rules, transparency and legitimacy for international actions to mitigate emissions across countries and industry sectors, including international emissions trading, and some hard-to-mitigate sectors, which need such opportunities. However, all these details for Article 6 proved not possible to agree at this COP, and when COP25 closed on Sunday afternoon (the longest over-run of a COP) they were passed to SBSTA (Subsidiary Body for Scientific and Technological Advice) in 2020 and COP26 (Glasgow) to pick up (which is now postponed).

IEAGHG at COP25

For IEAGHG, our primary focus was organising the UNFCCC Side-event with our collaborators the University of Texas, the International CCS Knowledge Centre, CCSA and Bellona. This was the only UNFCCC Side-event focussed on CCS. Titled "Carbon Removal and Return – Can CCS Decarbonise Industry in South America and Help the Oceans?" it was designed with CCS relevance in the original COP location in mind and a good gender balance. Tim Dixon provided the context of CCS in the UNFCCC environment, to remind attendees that the knowledge, rules and encouragement exist from UNFCCC for large-scale CO_2 reductions from safe and secure CCS.

The main scene setter was provided by Dr Carol Turley OBE on the new IPCC report on Oceans and Cryosphere, to re-emphasise that the oceans especially need CO_2 reductions from the atmosphere. This was followed by a talk on 'removal', ie Direct Air Capture, by Jen Wilcox, and then moving on 'return', i.e. capture and storage, with Katherine Romanak on proving storage security, Keith Whiriskey on CCS infrastructure, and Beth Hardy on their new collaboration on capture from cement plant in Alberta.

A new aspect was covered by Piera Patrizio of IIASA on the socio-economic value (including jobs) from CCS around regions of the world, especially BECCS in South America. An intended audience of this side-event was UNFCCC country delegates who are getting interested in whether they can use CCS in their own countries, and Andrew Jupiter showed how this is happening in Trinidad and Tobago, including their recent workshop which IEAGHG assisted with.

Speakers at the UNFCCC CCS side-event.
Photo courtesy of IISD/ENB | Diego Noguera (http://enb.iisd.org/climate/cop25/side-events/4dec.html)

As the only UNFCCC Side-event on CCS, the room was full, and the speakers stayed around afterwards continuing to answer questions with interested audience members. The event was covered by IISD and can be seen at https://enb.iisd.org/climate/cop25/side-events/4dec.html. There was also live streaming which will be available for some time afterwards at https://bit.ly/2DLVgsa.

IEAGHG also spoke at the CCP event on CCS Regulations, organised by Arthur Lee of Chevron. This event provided a good review of mature CCS regulations by Lee Solsbery of ERM, and taken right up to date with the requirements for 45Q, the Californian Low Carbon Fuel Standard, and CO_2 export. IEAGHG spoke at two more side-events in the second week. *"Transforming industry: Developing carbon capture, utilisation and storage clusters"* was co-organised by IEA and United Kingdom in the United Kingdom Pavilion, with Tim Dixon as a panellist on legal and regulatory aspects of clusters. This side-event included highlighting the Drax announcement on being net-zero with biomass and capture.

The Japanese event,"Saving Our Beautiful Planet with CCS (Part2)", was organised by Japan CCS Co, METI and NEDO in the Japan Pavilion, with Tim Dixon presenting on Sharing Learnings from Global CCS Developments and Projects. This event showcased the Tomakomai project reaching 300kt and its response to natural earthquakes, and Japan CCUS policy. The event had a good attendance for the last official day of COP.

Carol Turley, PML

Tim Dixon, IEAGHG

Beth Hardy, CCS International Knowledge Centre.

Keith Whiriskey, Bellona

Piera Patrizio of IIASA

Andrew Jupiter, University of the West Indies

All photos above by IISD/ENB | Diego Noguera (http://enb.iisd.org/climate/cop25/side-events/4dec.html)

London Protocol: Success in removing a legal barrier!

IEAGHG has been reporting to our members from the London Convention meetings (the UN-based global treaties that protect the marine environment) for over twelve years by attending and reporting by Information Papers and blogs. It is the only CCS-related organisation attending these meetings. As a reminder, a CCS amendment to the London Protocol was approved in 2006 and came into force in 2007 to allow storage in sub-seabed formations. A further CCS amendment was approved in 2009 to remove the prohibition on export of CO_2 for geological storage. The detailed work on the guidance on export of CO_2 and transboundary CCS was completed in 2012 (see IEAGHG Information Papers 2013-IP26 and 2014-IP19). However, for this 2009 export amendment to come into force, two thirds of the now 51 Parties to the London Protocol needed to ratify the amendment (i.e. 34). In terms of ratification progress, this had been extremely slow, with just 6 countries ratifying (Norway, UK, Netherlands, Iran, Finland and Estonia) over the ten years since, whilst the number of Parties had grown by 14 over the same period. This meant the legal barrier to exporting CO_2 from one country to another for offshore storage remained.

In 2011 the IEA produced a Working Paper "CCS and the London Protocol: Options for Enabling Transboundary CO_2 Transfer", with IEAGHG input. These legal options have more recently been presented and discussed at the 3rd Offshore CCS workshop in June 2018 (IEAGHG Report 2018-TR02) and at GHGT-14 session 11C. So in 2019 there was a formal proposal from Norway and the Netherlands (supported by UK) to use one of these legal options, and this was proposed to the 2019 London Convention meeting (LC41, 7-11 October 2019). This proposed option was a "Provisional Application" of the amendment between countries who desire to use it. This would allow them to proceed in exporting CO_2 to a secure offshore geological storage site, following the requirements and permit conditions described in the London Protocol's guidance documents so as to ensure the protection of the marine environment. The motivation for proposing this was that the Northern Lights project in Norway was seeking CO_2 from sources in other European countries. A drafting group was formed to work through and agree the details of the Resolution and proposed legal text, in which IEAGHG actively participated. The conclusion at the end of the week was that the Resolution for the Provisional Application was approved in Plenary. This removed the last significant international legal barrier to CCS, and means that CO_2 can now be legally transported across international borders to offshore storage.

A press release from Norway is available at https://www.regjeringen.no/no/aktuelt/eksport-av-CO2-for-offshore-lagringsformal-tillates/id2673809/ (in Norwegian). A press briefing from the IMO is available at http://www.imo.org/en/MediaCentre/PressBriefings/Pages/22-CCS-LP-resolution-.aspx. Also more detailed information on the proposal from Norway and the Netherlands is available from IEAGHG Information Paper 2019-IP11.

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, and consists of a Technical Group, a Policy Group, and Ministerial meetings. IEAGHG and the CSLF Technical Group have an agreed 'Collaborative Arrangement' since 2007.

The CSLF Technical Group has the following active task forces:

- CCS for Energy Intensive Industries,
- Non-EHR (Enhanced Hydrocarbon Recovery) Utilization,
- Hub and Infrastructure.
- Ad Hoc Committee for Task Force Maximization and Knowledge Sharing (will be renamed)
- Engagement of Academic Community

IEAGHG is one of the co-authors for Energy Intensive Industries task force report, and is contributing to Non-EHR, Hub and Infrastructure and Academic task forces.

The CSLF PIRT and Technical Group held meetings in Illinois in April and in Paris in November. IEAGHG gave an update of activities. Of note at the November meeting was the presentation of the final report from the Task Force on CCUS for Energy Intensive Industries (EIIs). The sectors considered were Steel, Cement, Chemicals, Refining, Hydrogen, Heavy Oil, Natural Gas, Fertilizer, and Waste to Energy. This work draws upon the IEAGHG reports relevant to these sectors, and IEAGHG's Monica Garcia was a co-author. There was also a half-day workshop on the 7th November at the same location to share this report, which IEAGHG assisted in organising. IEAGHG produced an Information Paper on the workshop outcomes, IEAGHG 2020-IP05.

Following the CSLF's Hydrogen and CCS report in June 2018, CSLF and IEAGHG organised a workshop on this topic, in collaboration with the IEA Hydrogen TCP and Equinor. The workshop was held on 6th November, 2019, Paris, France. The objective for IEAGHG was to identify R,D&D (Research, Development and Demonstration) needs for decarbonised hydrogen. IEAGHG produced a report of the workshop: IEAGHG Report 2020/TR01.

Mission Innovation

Mission Innovation CCUS Challenge held an expert workshop in Trondheim in June 2019. The workshop objective was to contribute in transferring early (low TRL) research activities to development and innovation activities (higher TRL) by developing guidance and development paths for emerging CCUS technologies and suggestions for new and joint development activities.

The final report was released and is available at the Mission Innovation website. IEAGHG was pleased to contribute two staff to the workshop, including the introductory speaker on industry CCS, as well as representation on the Steering Group. See IEAGHG Information Paper on the report, IEAGHG 2020-IP04.

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.

This ISO consists of six working groups: Working Group 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 in Caspar, Wyoming, from the 13-14th June 2019. IEAGHG provided an update.

IEAGHG International Research Network Activities / Reports 2019

Combined Monitoring Network and Environmental Research Network Meeting 20th – 22nd August 2019

The 13th meeting of IEAGHG's Monitoring Network was 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. It was followed by a one day workshop on faults and their significance for CO_2 storage (report number 2020-03).

The key sessions included: developments in sensing; lessons learned from managing field projects; uncertainty in quantification; monitoring for storage with EOR (enhanced oil recovery) compared with DSF (deep saline formation) requirements; what to do when primary techniques don't work; new case studies of real data; environmental impacts of monitoring; stakeholder engagement; upwell leakage; and monitoring post-injection for site closure.

The high level messages to come out of this meeting stressed the significant developments in marine and terrestrial sensing. Other views expressed highlighted the influence of social media and the necessity to respond to it. As a maintenance problem it should be accepted and dealt with. Long-term monitoring needs to be achieved with reliable tools and quantification is now attainable in marine environments. The main recommendations reached included the importance of learning from social scientists on how to communicate. The simplification of systems so they are appropriate for small operators was stressed as well as continued vigilance on detection, attribution and quantification.

Tim Dixon speaks at the Monitoring Network Meeting, University of Calgary, 20th August 2019.

Fault Workshop, 23rd August 2019, University of Calgary

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 this 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 one-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 one-day event documented critical issues for CO_2 storage related to faults, the experience of current experimental work, and identify remaining gaps in knowledge.

The key issues that emerged included the contribution from the petroleum industry which has significant experience in how to assess and estimate the sealing capacity of fault systems, especially in the geological timescales. These same concepts could also be developed for a CO_2 injection timescale. Experience shows that cross-permeability is important, as is up-dip permeability.

There is lots of experience and data on the lateral sealing of faults and the interaction of fault systems in 3D and fluid migration. The petroleum industry has experience of using technology for deriving fault gouge permeability based on the stratigraphy and basin history, along with experimental data.

There was a consensus that incorporating uncertainty is very important, as is modelling the uncertainty estimation. Current data is subject to bias towards fluids that are already trapped versus non-trapped and where to drill for success. There is also an exposure bias in faults, for example they are easily identifiable in road cuttings and outcrops, but the predictability of fault architecture in the subsurface can be less certain.

There are lots of models but little experimental data for CO_2 migration through faults. However, there are many experimental releases of CO_2 which are currently being planned at shallower depths, so the relevance to conditions at much deeper depths also needs to be considered. A key question to consider is the ranges of CO_2 and brine that could reach the surface, or other formations, under different storage conditions.

The workshop identified some areas for future investigation. These included the prediction of fault activity in basement rocks, more calibration and models and improving the ability to characterise the heterogeneity of faults and fractures. IEAGHG could work to help coordinate comparisons between future fault experiments.

CCS Cost Network Workshop, 19-20 March 2019, Palo Alto, California,

A meeting of the CCS Cost Network was hosted by EPRI in March 2019.

IEAGHG produced a report on the workshop that summarised the key messages. Please see report number 2019-06 Proceedings: CCS Cost Network 2019 Workshop on page 31.

Delegates listen to a presentation at the CCS Cost Network 2019 Workshop, Palo Alto, California, USA

Hydrogen Production with CCS Workshop, 6 November 2019, Chatou, France

Hydrogen is currently in an unprecedented momentum around the world and could be set as a pathway to reach decarbonisation goals in the power and industrial sectors. 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 workshops with other organisations.

A steering committee was formed to organise this workshop, held on November 6th 2019, and hosted by EDF and Club CO_2. 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:

- Define the Research, Development & Demonstration (RD&D) needs for decarbonised hydrogen
- Identify the role that decarbonised hydrogen can play in a future low-carbon society
- Provide recommendations on decarbonised hydrogen to policy-makers
- 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. The main conclusions highlighted that not only "blue" hydrogen production, but transport, storage, and use should be analysed. Moreover, while it is recognised that there is potential for blue hydrogen in the future economy, there are still a number of challenges to overcome. These improvements include: techno-economic performance; further deployment at large-scale; social acceptance; and integration within a regional or international supply chain. For these reasons, research and development is still needed, together with collaboration initiatives, plus regulatory and policy support, which will enable the presence of blue hydrogen in the future market. However, those challenges should not stop the deployment. The technology for "blue" hydrogen exists and can be implemented in a short -to mid-term perspective, thus forming a bridge to "green" hydrogen.

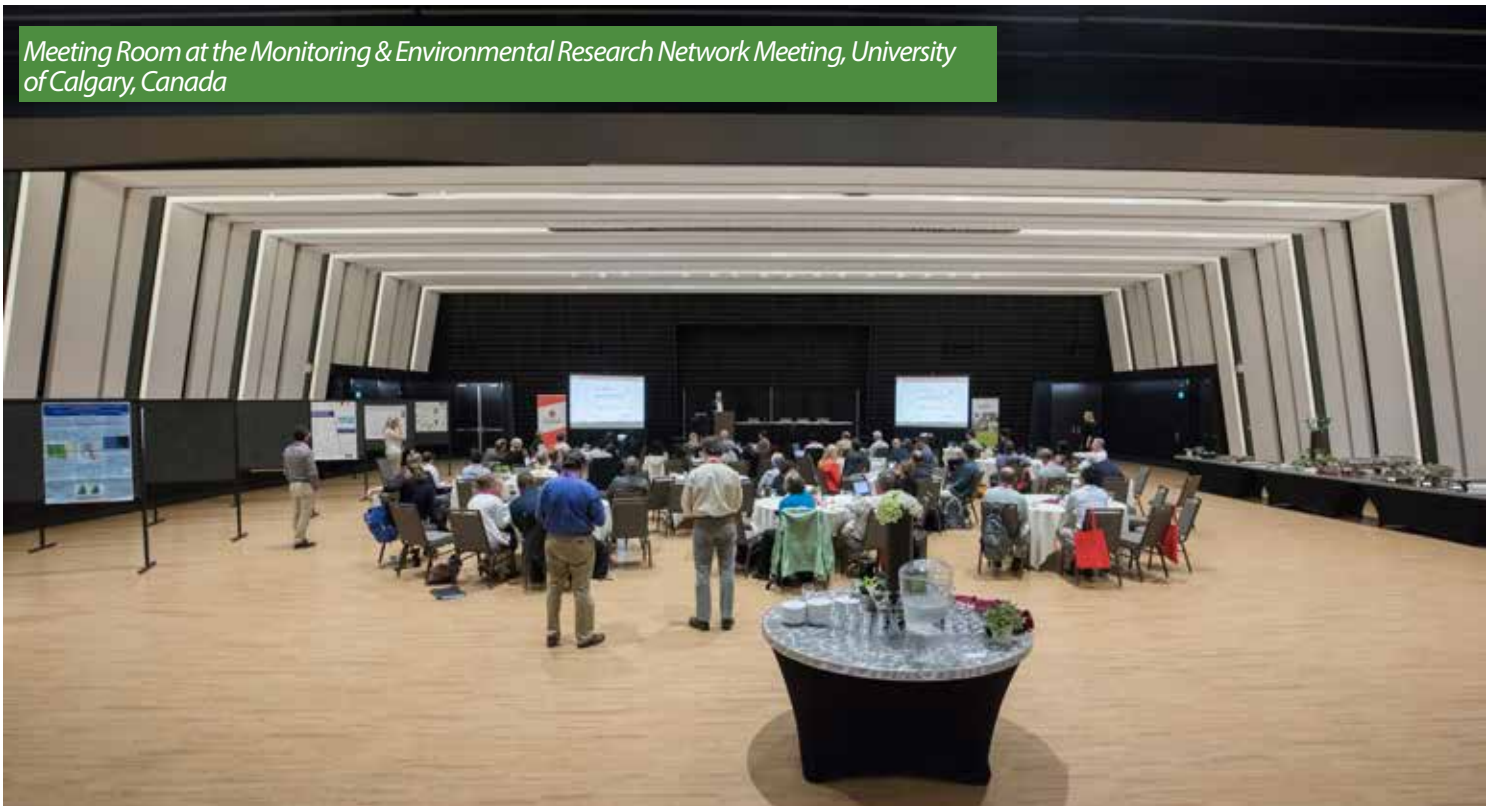
Recommendations

Immediate actions: Cooperation between countries, different industries and between industry and academia. Regulatory framework as a driver of the research, development, and innovation, which will catalyse the blue hydrogen deployment.
Medium-term actions: Application and deployment of hydrogen to niche opportunities for industry.
Long-term actions: Implementation of a complex infrastructure for hydrogen and CCS. Experience on long testing campaigns (e.g. safety, materials) and large-scale deployment.

IEAGHG delivered a summary of this workshop (IEAGHG 2020-TR01).

Delegates at the Monitoring & Environmental Research Network Meeting, University of Calgary, Canada

Meeting Room at the Monitoring & Environmental Research Network Meeting, University of Calgary, Canada



13th IEAGHG Summer School by Sam Neades

The 13th annual week-long IEAGHG CCS Summer School was hosted by the International CCS Knowledge Centre in Regina, Canada. This intensive 5 day event covered every aspect of CCS, from capture to storage and from health and safety to regulations and policy, giving a detailed overview to PhD students and early career professionals chosen to attend. IEAGHG were delighted to host the School with the Knowledge Centre again, following other successful Schools in Regina in 2016 and 2017.

Speakers from across the world visited the event to provide talks and mentoring to the 39 international students throughout the week, with 20 different countries represented by these students. On the Wednesday, the students and mentors were treated to a field trip to the Boundary Dam CCS project, with in-depth tours of the power plant, capture plant and CO_2 injection site (the Aquistore project). The ongoing School Series Sponsors (UK BEIS, Switzerland, Shell, CLIMIT and Total) were joined this year by local sponsors the International Brotherhood of the Boilermakers, Innovation Saskatchewan, MHI Japan, Stantec, Graham and PTRC.

Throughout the week, students attended lectures, undertook evening group work and presented posters on their own research; it certainly was a busy week! Two best posters were selected from the wide range presented: the winner, Viktor Stenberg (Chalmers University, Sweden) looked into 'Cost-effective large scale hydrogen production with net negative CO_2 emissions'; and in second place, Martijn van de Sande (from the Dutch Enterprise Agency, RVO, The Netherlands) presented his work on the 'Design of the Dutch CCS deployment stimulus'.

The group work done throughout the School culminated in presentations on the final day, where groups demonstrated a range of talents (including songs and interpretive dance!) to educate the audience on their particular topics, before being questioned about their subject area by a panel of experts. The winning group at this year's School tackled the topic of whether CCS has a role in the issue of 'unburnable carbon', giving an insightful, intelligent and somewhat comedic look into the issue.

Mennat Allah Labib from the University of Edinburgh, UK and Abdul Aziz Aliyu (the University of Sheffield, UK) won the two 'Most Outstanding Students' awards, sponsored by PTRC and the Knowledge Centre.

IEAGHG would like to express their thanks to the Knowledge Centre for again hosting such a wonderful and well-organised event, to the mentors and speakers who gave their time to contribute to the learnings throughout the week, to SaskPower for hosting us at Boundary Dam for our field trip, to our sponsors for the week and to the students whose enthusiasm, hard work and passion for CCS made this week definitely one to remember!

More information about the IEAGHG Summer School can be found by visiting the IEAGHG website: www.ieaghg.org

IEAGHG Technical Studies 2019

2019-01 Sustainability in Petrochemicals, report managed by Keith Burnard

Petrochemicals are an important building block of a huge range of products that underpin modern daily life and economic activity. With global demand likely to continue to grow, it becomes increasingly important to reduce the carbon footprint and increase the energy efficiency of petrochemicals production.

With a focus on methanol, olefins and ammonia/urea, this study explored potential options to produce petrochemical products in a more sustainable manner. The primary aim was to establish a methodology to assess different aspects of the sustainability of petrochemical production. The report investigates the impact of a combination of industry drivers on the historic, current and future status of the petrochemical industry. For each petrochemical explored, assessments were undertaken to gain insight into the sustainability prospects of the industry:

- **Market analysis**. An assessment of the historic and current status of market trade, including trends in end-uses, feedstocks, demand, production and international trade. Demand projections for each chemical are made based on collected data.
- **Process engineering characterisation** of the current and low carbon alternative routes and feedstocks to produce the key petrochemical productions.
- **Environmental life cycle assessment** of the various feedstocks and production methods for each petrochemical and a contribution analysis of the key environmental impacts.
- **Market projection** of petrochemical production and technology mixes for a key region, China, for the time period 2010 – 2050.
- A series of **expert stakeholder interviews** on views of how the petrochemical industry may progress in terms of demand, costs, environmental impacts and policy drivers.

Given the high regional variability in costs, feedstocks and processes that contribute to a strong global trade, substantial challenges to decarbonise petrochemicals were identified. And with ever-increasing demand, the implementation of an effective emissions policy was deemed vital to meet climate targets.

To decarbonise the petrochemical industry, low-carbon routes must be pursued via a combination of effective policy implementation, improved processes and a closing of the gap in costs when compared with mature fossil fuel options. From a technology perspective, a smaller carbon footprint may be achieved by improving the efficiency of a process, by developing innovative processes, by applying CCS, by employing suitable bio-based feedstocks and by deploying low-carbon hydrogen.

In relation to improvements of the methodology tested in this report, a number of recommendations have been made. Given the broad range of assessments included in this study, it was clear that a deeper and more insightful analysis could be achieved if the focus was narrowed, e.g. to focus on olefins or methanol or ammonia/urea, rather than explore all three.

2019-02 Towards Zero Emissions CCS from Power Stations Using Higher Capture Rates or Biomass, report managed by Keith Burnard

To-date, capture technology developers have largely focused on designing plant for CO_2 capture rates of 85% to 90%, leaving 10-15% of the emissions uncaptured, which are usually referred to as residual emissions.

In fact, in recent years, a 90% capture rate cap has featured almost ubiquitously, e.g. in integrated assessment models, in

advanced project initiatives and FEED studies, as well as in the two large-scale CCS projects operating at present in the power industry. It has been shown, however, that in a "well below 2°C" scenario, it would be virtually impossible to achieve the net zero carbon emissions projected to be required in the second half of this century without substantially higher capture rates. This study was commissioned to explore the potential for the residual emissions from capture technologies to approach zero.

This study was commissioned to explore the potential for the residual emissions from capture technologies to approach zero.

A review of the literature indicated that, qualitatively, there were no technical barriers to substantially increasing capture rates in the three classic capture routes (post-, pre- and oxyfuel combustion) and with the broad suite of CO_2 capture technologies currently available or under development. A techno-economic analysis of a standard PCC process using monoethanolamine (MEA) solvent applied to both coal- and gas-fired power plants revealed that, with dedicated process design, the additional costs of achieving essentially zero CO_2 emissions (99.7% for coal and 99% for gas) were quite modest in comparison with the costs of achieving 90% CO_2 capture.

Importantly, it was also found that, as CO_2 capture rates are increased, indirect emissions from fossil fuel use become significant, i.e. as the direct emissions tend to zero, the indirect emissions become proportionately greater. To maximise the benefits of higher CO_2 capture rates in providing a path towards zero emissions, increasing the capture rate should therefore go hand-in-hand with effective management to reduce overall CO_2 emissions, particularly in the fuel supply chains.

Although biomass is an important source of the world's primary energy requirements, only a small portion (~4%) of bioenergy is used for power generation globally. Combustion is the dominant and proven technology for (heat and) power generation from biomass. Co-firing biomass in existing coal-fired power plants is a simple and effective way to reduce CO_2 emissions. In fact, for coal-fired power stations, the option of using a combined biomass co-combustion (10% biomass) with a standard PCC process (90% CO_2 capture) was the lowest cost option for effectively achieving zero CO_2 emissions.

2019-03 Review of Fuel Cell Technologies with CO_2 Capture for the Power Sector,
report managed by Monica Garcia

Carbon capture systems are needed within the mix of measures for decarbonisation. Pre-, oxy- and post-combustion technologies appear as advanced systems, but the energy penalty and consequent efficiency drop are still large concerns.

Electrochemical conversion with fuel cells (FCs) has been proposed as a more efficient carbon capture option. Two types of fuel cells, Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs) have recently emerged as alternatives to capture CO_2 with the advantage of additional power production.

The results from this study show that fuel cells have the economic and technical potential to compete with current benchmark technologies for CO_2 capture. Although due to the lack of demonstration projects which can give realistic inputs to the cost estimations these results have a significant uncertainty. This study homogenized costs figures in the literature for different fuel cells configurations.

The MCFC case operating at atmospheric pressure in a NGCC (Natural gas Combined Cycle) plant, with a CO_2 capture system using oxy-combustion followed by condensation, offered the lowest CO_2 avoidance cost.

In this study, the fuel cell investment cost has the highest impact on the LCOE and CO_2 capture cost. The cost of the fuel cells can be divided into material and component costs, labour, and the capital cost of manufacturing. Labour, capital and manufacturing costs can be reduced through economies of scale in manufacturing. However, material and component costs are dependent on technological innovations and the market. For the other components, steel, nickel, zirconia and other materials could impact the stack cost but that can also decrease through manufacturing cost reductions. Utilities and other components contribute to a large portion.

The fuel cell stack life was identified in the literature as a significant parameter impacting on LCOE and CO_2 capture cost. However, in this study, it was observed that this contribution is less significant than the fuel cell investment cost.

Working under pressurized or atmospheric conditions will impact on the costs and must be considered as a design parameter. While an increase on the working pressure will increase the efficiency, that will also add some complexity and additional installed costs due to added auxiliary equipment and more expensive materials.

In terms of operational challenges, pressure management is key for a safe operation, where materials and pressure control will be key. Moreover, if further purification is done through oxy-combustion, oxygen handling will demand some attention. Costs will be influenced by the fuel cell performance, which is affected by operation parameters such as the current density, gas composition, fuel utilisation, pressure and temperature.

Although this study shows that fuel cells are promising solutions to tackle CO_2 emissions in the power sector, the high investment, operation costs and auxiliaries contribute to a high LCOE and CO_2 capture cost. Challenges and barriers can be split into: manufacturing and materials; operation; public policy and large scale CCS deployment. Based on the early stage of commercialization of fuel cells, these systems still require financial support (e.g. grants, enhanced depreciation allowances, feed-in tariffs and fuel discounts). Policy mechanisms are essential and robust and comprehensive regulatory frameworks will promote their CCS deployment.

2019-04 The Shell Quest Carbon Capture and Storage Project,

report managed by James Craig

In late August 2015, Shell Canada began sustained, commercial-scale operation of the first-ever CO_2 capture facility at an oil sands bitumen or heavy oil upgrader in the world, as well as transportation and storage of the carbon dioxide to a nearby geological storage site.

This remarkable facility is situated near Edmonton, Alberta, Canada. This report explores the journey of the Shell Quest Carbon Capture and Storage Project team and its partners, and will provide valuable insights to other heavy oil upgraders and oil refineries globally that seek to reduce their lifecycle greenhouse gas emissions through deployment of CCS technologies and infrastructure.

The Shell Quest project was conceived in 2008 and began early operation seven years later. During this period, Shell Canada and its project team achieved many firsts:

- design, construction, and operation of an efficient, operating amine capture facility at an oil sands upgrader,
- transportation of the produced CO_2 to a suitable site for long-term storage at a nearby deep saline aquifer geological formation within 64 km of the Scotford Upgrader,
- development, deployment and management of a world-class geological storage site, and
- attainment of local, regional, national and international key stakeholder support and engagement for the undertaking.

This project was a ground-breaking achievement. Until it was operational, no other heavy oil upgrader or refinery in the world had deployed carbon capture and storage (CCS) to reduce its carbon footprint. Consequently, as of 2015, Shell Quest has provided a sustainability benchmark to the oil industry.

2019-05 CCS in Energy and Climate Scenarios, report managed by Keith Burnard

Integrated assessment models (IAMs) quantify the interactions and trade-offs between societal demands for energy, economic, and environmental services, using a systems approach. These systems are typically the energy system, the economy, the earth-land system, the water system and atmospheric climate system, although every IAM does not necessarily include all these systems and have varying degrees of completeness or complexity.

The mathematical approach underpinning each IAM can vary across the models. Classifications include whether a model's equations finds a partial equilibrium or general equilibrium between supply and demand, whether or not the model is attempting to optimise or simulate, the range of sectors included in the model, the treatment of discounting of costs, the temporal resolution and treatment of foresight; all of these influence the model dynamics and responsiveness in differing ways. Each IAM has its own strengths and weaknesses.

Some industry medium-term models based on econometric simulation techniques describe their analysis as outlooks, implying a level of forecasting accuracy, while most research long-term IAMs do not claim to have forecasting capabilities as the future is too uncertain, and instead gain insights by describing sets of potential futures under scenario analysis covering a broad range of uncertainty in input assumptions.

CCS is represented in most IAMs and plays a key role in a large number of energy and emissions scenarios. While IAMs often align on high level messaging about the value and need for CCS, the actual role, impact and applications (e.g. power vs industrial, coal vs gas, CCS vs BECCS) vary considerably. Due to the nature of scenario making, the input data, background calculations and assumptions are not always presented in a clear and transparent way together with the results. This can result in confusion and a lack of appreciation of the value of CCS (in both general and specific applications) within the energy sector, e.g. with manufacturers, policy makers, regulators and the general public. Inaction or inappropriate action is often the result.

It is also important to note that, while global results are often presented, for most policy makers it is the projections for countries and regions that are most meaningful. Thus the geographical granularity that underpins any particular IAM is of crucial importance. In many IAMs, this is not adequately addressed.

The aim of this study, undertaken by a consortium comprising University College Cork (study lead), Imperial College London and the University of Oxford, is to provide insight as to why the projections and outcomes for carbon capture and storage might differ among a selection of the more influential IAMs, by exploring the assumptions, background calculations and input data. The purpose of the study is to provide a transparent approach to understanding model results. It is not the intention of the study to advocate particular scenarios.

2019-06 Proceedings: CCS Cost Network 2019 Workshop, report managed by Keith Burnard & Monica Garcia

The sixth meeting of the CCS Cost Network Workshop was held on March 19-20, 2019 at the Electric Power Research Institute (EPRI) headquarters in Palo Alto, California, under the auspices of the IEA Greenhouse Gas R&D Programme.

The purpose of the workshop is to share and discuss the most current information on the cost of carbon capture and storage (CCS) in electric utility and industrial process applications, as well as the outlook for future CCS costs and deployment. The workshop also seeks to identify other key issues or topics related to CCS costs that merit further discussion and study.

As in past workshops, Day 1 was devoted to a plenary session addressing four general topics. Each session included two or three invited presentations, followed by a discussion among workshop participants. The second day began with a fifth plenary session topic, followed by three parallel breakout sessions pursuing selected topics in more detail. Reports of the breakout groups were presented in a final plenary session, followed by general discussion of lessons learned and planning for future events.

This report presents brief summaries of the five plenary session topics, together with the full set of presentations by invited speakers. The proceedings of this and all previous CCS Cost Workshop are available online from the IEAGHG website.

2019-07 Techno-Economic evaluation of CO_2 Capture in LNG Plants,
report managed by Jasmin Kemper

Natural gas (NG) is projected to play a vital role in the energy mix of the 21st century. Its demand is forecasted to grow 2.5% a year for the next 10 years, ranking it second in the global energy mix in 2030. This study was commission to provide a technical evaluation and cost assessment of capturing CO_2 contained in produced natural gas and also CO_2 emitted by fuel combustions for power generation for LNG trains and refrigerant cycle compressors in liquefied natural gas (LNG) plants, including small scale (SSLNG) and floating (FLNG) plants.

Prior to this study there was a lack of information on CO_2 capture in LNG plants. Consequently, the results of this study will be of direct interest to developers of LNG projects, the related capture technology, as well as vendors and policy makers.

Key Messages

- Although pre-combustion and oxyfuel options are available for capturing fuel related CO_2 emissions, post-combustion CO_2 capture, using well proven chemical absorption technology, will be the preferred route for baseload LNG (with a liquefaction capacity of 4.6 mtpa, 2mol% feed gas, state-of-the-art C3MR refrigeration process, proprietary amine CO_2 capture and located on the US Gulf Coast), as it can be installed without affecting the performance of the core process. This option reduces technical risks and process complexity.
- The cost of CO_2 captured for a baseload LNG plant (as described above) was estimated at €47.3/tCO_2 with the cost of CO_2 avoided at €55.2/tCO_2. The levelised cost of LNG for the baseload LNG plant without CCS is €1.18/MMBtu (or €54.5/tLNG), with CO_2 capture this cost increases by ~20% to €1.41/MMBtu (or €65.4/tLNG).
- The total range of cost encountered during the sensitivity analysis was €13 - €57/tCO_2 for the capture cost and €14 - €78/tCO_2 for the avoidance cost. A CO_2 emissions price of at least €129/tCO_2 would be required to make the base case LNG plant with CCS economically feasible.
- A CO_2 capture design that is incorporated into an exclusive acid gas removal unit (AGRU), instead of capturing the fuel related emissions as well, could bring down costs significantly to about €30/tCO_2. This figure is more in line with current CO_2 prices in certain countries, for example Norway and Finland, which indicates the potential for the implementation of CCS.
- Both SSLNG and FLNG plants have comparatively limited global capacity and therefore limited global CO_2 emissions. Global CO_2 emissions from SSLNG are an order of magnitude smaller in comparison with emissions from baseload LNG plants and three orders of magnitude smaller than global CO_2 emissions from power plants (8 - 10 mtpa vs 75 - 100 mtpa vs 10,000 mtpa). In addition, application of currently available CO_2 capture technologies face severe technical as well as economic challenges in these plants. Thus, efforts should focus on CCS in baseload LNG plants with capture capacity plants of around 3,000 t/CO_2 day equivalent to 1 mtpa.
- Large scale LNG trains (such as those found in Qatar with a capacity of 7.8 mtpa LNG) may provide greater benefits for CO_2 capture as a result of economies of scale. The total capture cost for plants this size is reduced by 12% with respect to the base case to about €41.6/tCO2 and avoidance cost reduced to about €48.4/tCO_2.
- Recommendations for further work include:
  - Pursuing general efforts to make CO_2 capture systems more efficient
  - Assessment/development of other capture technologies as suitable for LNG
  - Developing strategies to reduce compression power requirement
  - Improving thermal efficiency of liquefaction process, e.g. through use of electric motor drives
  - Developing exhaust gas recycle (EGR) technology with particular focus on gas turbines in LNG
  - Demonstrating CCS in LNG on the fuel gas combustion processes

2019-08 Proceedings: Workshop on Representing CCUS in Energy Systems Models, report managed by Keith Burnard

The USDOE's Office of Fossil Energy convened a workshop on 17-19 October 2018 in College Park, Maryland, USA, to provide a forum to review and exchange the latest understanding of carbon capture utilisation and storage (CCUS) and to improve the modelling approaches and representation of CCUS in energy systems models (ESMs) and Integrated Assessment Models (IAMs).

This was the second workshop on this theme, following a previous workshop also hosted by US DOE-FE on 3-4 April 2017 in Washington DC, USA. This second workshop was designed to grow and expand the number of research groups with expertise in up-to-date modelling of advanced fossil technologies and related market impacts, including application of US National Energy Technology Labs (NETL) cost and performance baseline data and CCUS expertise, tax implications of 45Q, EOR market feedback and information on international markets. It also sought to create a community of practice and to link CCUS technical experts with modellers and analysts.

The workshop attracted CCS technology experts, CCS data providers, CCS process engineers and relevant stakeholders, together with ESM and IAM modellers from policy, industry and academia. The attendees were largely from the USA, all of whom had been studying CO_2 capture, utilisation and storage.

Accurate data provision was the core issue echoed at this workshop, repeating one of the outcomes from the April 2017 workshop. Data flow from CCUS technical experts to process modellers and onwards to energy systems and integrated assessment modellers is the mechanism that joins these communities of researchers and analysts. It is critical that the transaction cost between CCUS and modellers is reduced. While NETL's recent release of new baseline process model databases was identified as a way of bridging this gap, some modellers lacked the expertise to interpret and appropriately utilise the data, illustrating the importance of dialogue between technologists and modellers. Many models still lack the capability to address fiscal implications of 45Q policy, or to represent the temporal dynamics of partial load CCS plants and the resultant variable capture rates from CCS plants.

There were many expressions of interest in holding similar workshops. Considerable work remained to develop an effective network and to establish a robust community of practice that extended from technical research to integrated analysis capabilities.

IEAGHG are working with IEA-ETSAP (Energy Technology Systems Analysis Program) to identify a process for sharing up-to-date CCUS data with IEA-ETSAP's ongoing energy technology database project. NETL are also a critical data provider and their engagement in this process would be encouraged.

2019-09 Further Assessment of Emerging CO_2 Capture Technologies for the Power Sectors and their Potential to Reduce Costs report managed by Monica Garcia

New Carbon Capture technologies are emerging and these must be techno-economically compared with well-established systems used for the power sector. IEAGHG identified the need of a comprehensive assessment of emerging CO_2 capture technologies for this sector, and an evaluation of their potential to reduce costs.

The objectives of this technical study were:

- To update the CO_2 capture benchmark technology and its enhancement over the adopted 30w.t.% MEA (Monoethanolamine) -based chemical absorption technology currently used.
- To review the CO_2 capture technologies used in the power sector, their current status and trajectory.
- To assess the potential of emerging CO_2 capture systems to reduce the Levelised Cost of Electricity (LCOE); and identify risks and barriers on the path of different technologies to reaching TRL 9 (full commercial operation).
- To assess techno-economically a number of selected CO_2 capture technologies for coal and gas-fired power plants.

The techno-economic review covered calcium looping, membrane-system (MTR Polaris), Allam cycle, and chemical absorption (using 30w.t.% MEA (Monoethanolamine) and 40w.t.% PZ (Piperazine) + AMP (2-amino-2-methyl-1-propanol) solution) for gas-fired power plants, and calcium looping, membrane-system (MTR Polaris), solid sorbent-system (Veloxotherm), liquid-liquid separating system (DMX), and chemical absorption (using 30w.t.% MEA and 40w.t.% PZ+AMP) for coal-fired power plants. Coal-fired and gas-fired power plants without CO_2 capture systems were assessed for comparison.

The following key messages are evident from this study:

- A (PZ + AMP) solution (40w.t.%, 1:2 Molar ratio) is proposed as the new benchmark.
- The new benchmark solution (PZ+AMP) shows a CO_2 avoidance cost reduction of 22% for coal-fired, and 15% for gas-fired power plants, compared to a 30w.t.% MEA-based system. The reboiler heat duty (heat energy required to regenerate the solvent) of the new benchmark is similar to that of current commercial blends.
- Chemical absorption is still leading the list of emerging CO_2 capture technologies as it has reached TRL 9 compared to the lower TRLs of other technologies.
- This study has investigated the progress of several post-combustion systems and shown further technological development is possible. Moreover, oxyfuel turbines are expected to advance in the near future.
- Front-end engineering design (FEED) research studies show that there is significant potential to reduce the LCOE in electrochemical separation (fuel-cells). An estimated 30% reduction in the LCOE has been predicted but this claim requires confirmation through large-scale demonstration projects.
- Other capture systems with medium LCOE reduction potential (10%-30%) are based on chemical absorption with water-lean, precipitating or catalysed sorbents, membrane separation, PSA (pressure-swing adsorption), TSA (temperature-swing adsorption), calcium looping, and cooling and liquefaction. Moreover, pressurized oxyfuel combustion, chemical-looping combustion and SEWGS (sorption-enhanced water-gas shift) are also expected to show some LCOE reduction (<10%).
- The techno-economic assessment shows the impact of regional, financial and economic conditions on the LCOE obtained by the different CO_2 capture technologies applied to gas-fired and coal-fired power plants.
- For coal-fired power plants, the new benchmark solution (40w.t.% PZ + AMP) shows the lowest LCOE, while the Allam cycle would be, economically, the most favourable option for gas-fired power plants. However, in both gas and coal-fired power plants the other CO_2 capture alternatives could be more favourable under specific financial and economic conditions.
- Based on the results from this study, it is recommended that the most promising technologies should be followed-up, and more detailed cost evaluation studies pursued, together with an evaluation of their extended value within electricity supply, grid distribution and broader decarbonisation goals.

2019-TR01 Guide to Front End Engineering Design Studies for Selected CO_2 Capture and Storage Projects report managed by James Craig

There is a considerable amount of background material published on CO_2 Capture and Storage (CCS) demonstration projects, including capital (CAPEX) and operational (OPEX) costs which can be helpful for comparison with new projects. However, this material is often widely distributed and not easy to find or conveniently located. IEAGHG have produced a guide for locating key references of selected Front End Engineering (FEED) design studies for (CCS) projects. Its primary aim is to provide a convenient source of key references for these FEED studies with a specific focus on technical and cost information that are in the public domain.

The guide also includes a brief summary of cost information for four high profile demonstration sites that have either been planned, or in one case built and operated. They include: Peterhead – Goldeneye; Quest, White Rose and Mountaineer. A brief commentary on the basis for the cost ranges presented, and the percentage variation applied in each example, is also covered. The derivation of cost estimates shows that there are differences in approach and levels of accuracy. If this information is important a direct approach to the lead developer is recommended.

The level of detail and availability of FEED studies varies considerably. Some documents are publically accessible and can be downloaded from internet websites, whereas other material is held by lead developers who would need to be approached. The FEED guide lists major CCS projects where FEED studies are known to exist and includes relevant contact details.

2019-TR02 CO_2StCap (Cutting Cost of CO_2 Capture in Process)

report managed by Monica Garcia

A capture rate above 90% is technically feasible and relatively cost-effective in some cases within the power production sector. However, in specific areas such as in process industries, this capture rate could imply an excessive cost, potentially due to the large amount of energy required, heat or steam demand, and the complex connections to capture the CO_2 from several CO_2 stacks.

The main objective of the CO_2StCap project was to investigate CO_2 capture at partial rates as a way to achieve significant CO_2 capture cost reductions at acceptable CO_2 emissions reduction levels. The CO_2StCap project focused the research on the following industries: cement, pulp and paper, steel and silicon for solar cells. The pathways investigated were: integration of the CO_2 capture system within a dynamic energy system; use of partial capture rate; and the use of biomass.

2019-TR03 Integrated Greenhouse Gas Accounting Guidelines for Carbon Dioxide, Capture, Utilisation and Geological Storage 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.

IEAGHG 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 2019, 9 technical reports and 3 technical reviews were published (see page 26 for overviews or 37 for the list).

The IEAGHG Blog

www.ieaghg.org/publications/blog

The IEAGHG blog 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 Programme published 35 blogs during 2019.

Information Papers

http://ieaghg.org/publications/information-papers

Information Papers (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 15 IPs in 2019.

IEAGHG Social Media

https://twitter.com/IEAGHG
www.linkedin.com/groups/IEAGHG-4841998
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 2018 Annual Review....

2038 Followers (15% increase)

facebook
1519 Likes (1.75% increase)

LinkedIn
907 Group Members (7% increase)

IEAGHG Webinars

Webinars have now become a staple in our knowledge sharing cupboard. These have continued to prove a popular source of communication and allow us to get information out quickly and to a broad audience. 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 to be included.

Webinar Title & Description	Date	No. Attendees	No. YouTube Views to Date
COP-24 Summary Highlights - An Incomplete Paris Agreement Rule Book At COP24 Katowice, after three years of negotiations of the Paris Agreement Work Programme ("rule book"), which would provide many more details to the framework, Parties were able to complete a majority of the agreement. However, the implementation details of Article 6 "Cooperative Approaches" were left unfinished with several fundamental differences of positions between Parties. Article 6 would set out how Parties and the economic sectors of Parties could cooperate with each other via market-based and non-market based approaches. For many businesses, market-based mechanisms would be similar to enabling such policies as the European Union Emissions Trading Scheme, or sub-national emissions trading schemes in the U.S. and Canada, and other carbon pricing regimes being established to coordinate and link with each other to lower the cost of transactions, increase the opportunities for emissions reductions & possibly also raise the level of ambition globally. COP25 will now have to take up the completion of this part of the Paris rule book.	10/01/19	34	237
The CO2stCAP Project and Overall Results The CO2stCap-Project is a Norwegian-Swedish research initiative initiated in 2015 to reduce the cost of carbon capture in the process industry by developing concepts for partial capture. The project focuses on four industrial processes that have process-related emissions of CO_2 - that is, emissions are not only from heat supply but also part of the manufacturing process. Such emissions are likely to require CCS as they are difficult to reduce by measures like fuel-shift, electrification, or energy efficiency improvements. The project has showed that partial capture may reduce the cost for CO_2 capture, and can be a first step for moving CCS forwards.	25/06/19	41	140
Effects of Plant Location on the Costs of CO_2 Capture The cost of CO_2 capture is often cited as a single value or as a range, regardless of design, ambient conditions or location. For many, greater granularity on the regional differences in costs would be of value. Incomplete information can lead to flawed analysis and result in poorer decision making. This study was commissioned to investigate how the cost of CO_2 capture varied for different locations. The performance and costs of the power plants were assessed and quantified according to local and site specific conditions. The study provides a comprehensive assessment of the performance and costs of supercritical pulverised coal and natural gas combined-cycle power plants, with and without CO_2 capture, in geographical regions that exhibit a wide variety of local conditions. It provides insights of value to decision makers, project developers and the broader CCS community. In particular, the results of the study will provide a valued source of input data for the integrated assessment model community, whose outputs often serve to inform energy policy decisions and the direction of energy funding.	17/10/19	31	56

Table 1: List of 2019 Webinars

Technical Reports, Technical Reviews, Information Papers and Blogs

Report No.	Technical Report Title	Issue Date
2019-01	Sustainability in Petrochemicals	11/02/2019
2019-02	Towards zero emissions from CCS	20/03/2019
2019-03	Review of Fuel Cell Technologies with CO_2 Capture for the power sector	18/04/2019
2019-04	The Shell Quest Carbon Capture and Storage Project	19/09/2019
2019-05	CCS in energy and climate scenarios	10/07/2019
2019-06	Proceedings of 6th CCS Cost Network	11/07/2019
2019-07	CO_2 capture in LNG plants	04/10/2019
2019-08	Proceedings: Workshop on Representing CCUS in Energy Systems Models	19/08/2019
2019-09	Further Assessment of Emerging CO_2 Capture Technologies for the Power Sector and their Potential to Reduce Costs	02/10/2019

Table 2: List of 2019 Technical Reports

Review No.	Technical Review Title	Issue Date
2019-TR01	Guide to Front End Engineering Design Studies for Selected CO_2 Capture and Storage Projects	16/09/2019
2019-TR02	CO_2StCap (Cutting Cost of Capture in Process Industry)	18/11/2019
2019-TR03	Integrated Greenhouse Gas Accounting Guidelines for Carbon Dioxide, Capture, Utilisation and Geological Storage	14/11/2019

Table 3: List of 2019 Technical Reviews

IP No.	Information Paper Title	Author	Issue Date
2019-IP01	IEA, the energy mix - CO_2 emissions still rising	NA	08/04/2019
2019-IP02	CONFIDENTIAL	TD	08/04/2019
2019-IP03	The Committee on Climate Change and their report on the UK's contribution to stopping global warming	SN	13/05/2019
2019-IP04	CCT2019 - Session on hydrogen production with CO_2 capture	MG	11/06/2019
2019-IP05	CCUS Outcomes at G20 Ministerial	SN	28/06/2019
2019-IP06	CONFIDENTIAL	KB	03/07/2019
2019-IP07	CONFIDENTIAL	JC	03/07/2019
2019-IP08	CONFIDENTIAL	TD	03/07/2019
2019-IP09	CONFIDENTIAL	KB	10/07/2019
2019-IP10	CONFIDENTIAL	KB	15/07/2019
2019-IP11	Positive Developments on the London Convention's Export Amendment	TD	19/08/2019
2019-IP12	CSLF Pore Space Utilisation report	SN	26/09/2019
2019-IP13	CCUS and EIIS Workshop	MG	11/12/2019
2019-IP14	CONFIDENTIAL	KB	19/12/2019
2019-IP15	COP25 - Lack of Progress on International Arrangements and Other News	TD	20/12/2019

Staff Abbreviations:
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KB: Keith Burnard
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NA: No author
SN: Samantha Neades
TD: Tim Dixon

Table 4: List of 2019 Information Papers

Blog Title	Author	Issue Date
CCS Technical Workshop 2019, Tokyo	TD	25/01/2019
Gulf of Mexico Offshore Projects First Annual Meeting	TD	13/02/2019
CCUS Roundtable to input to G20 - Strengthening International Collaboration on Carbon Capture Use and Storage	TD	18/02/2019
Developing Environmental Monitoring for Offshore CO_2 Storage Projects - One experiment, two ships, lots of measurements means the North Sea in May will be an exciting place!	TD	04/03/2019
IEAGHG CCS Cost Network Workshop	KB	22/03/2019
Insights from Illinois – CSLF and MGSC Meetings: 45Q ideas, NetPower update, award for SECARB	TD	01/05/2019
New IEAGHG Technical Report - 2019-03 Review of Fuel Cell Technologies with CO_2 Capture for the Power Sector	MG	13/05/2019
IEAGHG's 55th Executive Committee Meeting: site visit to Neste's refinery in Porvoo, Finland	JK	14/05/2019
Ralph Keeling at the Oxford Climate Society	TD	04/06/2019
CCT2019 - a great opportunity to know more about the status of CCS in coal power plants	MG	19/06/2019
ADB – DeepDive Workshop 20th – 21st June 2019	JC	03/07/2019
New IEAGHG Technical Report: 2019-05 'CCS in Energy and Climate Scenarios'	KB	10/07/2019
Final meeting CO2 stCAP project	MG	10/07/2019
New IEAGHG Technical Report: 2019-06 'Proceedings: CCS Cost Network 2019 Workshop'	KB	11/07/2019
IEAGHG Summer School 2019	SN	18/07/2019
Carbon Management Technologies Conference (CMTC 2019)	MG	31/07/2019
New IEAGHG Technical Report: 2019-08 'Workshop on Representing Carbon Capture Utilisation and Storage in Energy Systems Models'	KB	20/08/2019
Site visit to CaMI (Containment and Monitoring Institute Research Site), Tuesday 20th August 2019	JC	27/08/2019
Fault Workshop – University of Calgary, Friday 23rd August, 2019	JC	27/08/2019
Monitoring and Environmental Network meeting	TD	27/08/2019
CCUS and Oil & Gas Gas Technologies Integrated Review Meeting – Pittsburgh 26th – 30th August	JC & TD	29/08/2019
NETL development of Monitoring Technologies	JC	29/08/2019
NETL-Supported CarbonSAFE Projects Research	JC	29/08/2019

Table 5: List of 2019 Blogs

Blog Title	Author	Issue Date
International Value Chain Developments Panel at Pittsburgh	TD	03/09/2019
News from the European High Level Conference on Carbon Capture and Storage	TD	06/09/2019
Achieving Net Zero Conference, Oxford	TD	12/09/2019
PCCC-5	MG	27/09/2019
New IEAGHG Technical Report: 2019-09 'Further Assessment of Emerging CO_2 Capture Technologies for the Power Sector and their Potential to Reduce Costs'	MG	02/10/2019
Positive Result on the London Protocol's CCS Export Amendment	TD	22/10/2019
3E Research Symposium at the Bureau of Economic Geology	TD	31/10/2019
International Knowledge-Sharing Symposium in Trinidad and Tobago	TD	31/10/2019
Isabelle Czernichowski-Lauriol of BRGM Awarded the Prestigious Legion of Honour Award	BK	07/11/2019
An 'Impression' of the CSLF Technical Group meeting, Chatou, Paris	TD	07/11/2019
CCUS 2019: "Capturing the Clean Growth Opportunities"	KB	08/11/2019
IEAGHG Executive Committee meeting - Visits to Petra Nova and NET Power facilities	MG	22/11/2019

Staff Abbreviations:

BK: Becky Kemp
JC: James Craig
JK: Jasmin Kemper
KB: Keith Burnard
MG: Mónica García
TD: Tim Dixon
SN: Samantha Neades

Table 5: List of 2019 Blogs continued

Presentations made in 2019

Presentation Title	Location	Speaker	Date
International Scene-setting on Offshore CCS	GoMCarb & SECARB Joint Partnership Meeting	TD	11-12/01/2019
Current States of Legislation and Regulation on CCS	CCS Technical Workshop, Tokyo	TD	16/01/2019
Progress on Global Acceptance of CCS as GHG Mitigation Measure	Shell Science Council, Bangalore, India	TD	30/01/2019
Biomass with carbon capture and storage (BECCS/Bio-CCS)	Guest lecture for MSc course, Imperial College London, UK	JK	06/02/2019
Update on Carbon Dioxide Capture Utilization and Storage in the Global Climate Scene	IEAGHG and Bureau of Economic Geology -University of Texas at Austin	TD	15/02/2019
IEAGHG-IEA cost review on CO_2 capture in cement and steel production	IEAGHG Cost Network, California	MG	19/03/2019
Update on Carbon Dioxide Capture and Storage in the Global Climate Scene	Peabody, St Louis	TD	23/04/2019
Update on Carbon Dioxide Capture and Storage in the Global Climate Scene	Midwest Carbon Sequestration Science Conference, Champaign	TD	24/04/2019
Update Report from IEAGHG	CSLF Technical Group, Champaign	TD	25/04/2019
An update of CO_2 capture technologies for coal power plants, their potential to reduce costs and the flexible integration in the electricity grid: an overview of recent IEAGHG studies	CCT 2019	MG	03/06/2019
CCS in Energy and Climate Scenarios	ZEP Network Technology Meeting, Brussels, Belgium	KB	04/06/2019
Global Perspective	CO2stCAP, Trondheim, Norway	MG	13/06/2019
Further Assessment of Emerging CO_2 Capture Technologies and their potential to reduce cost	Gassnova, Trondheim, Norway	MG	14/06/2019
Keynote: Update on CCS in Global Climate Scene	TCCS-10, Trondheim, Norway	TD	18/06/2019
Review of Current and Emerging CO_2 Capture Technologies	TCCS-10, Trondheim, Norway	MG	18-19/06/2019
IEAGHG-IEA Technical Study: Homogenized Cost Review of CO_2 Capture in the Cement and Iron and Steel Industries	TCCS-10, Trondheim, Norway	MG	18-19/06/2019
Decarbonizing Industry Sectors (Power, Cement, Refineries, Steel, Fertilizers,…)	Mission Innovation Challenge #3 – CCUS, Trondheim, Norway	MG	19-20/06/2019

Table 6: List of 2019 IEAGHG Presentations

Presentation Title	Location	Speaker	Date
GHG emissions accounting for CCU technologies	17th International Conference on Carbon Dioxide Utilization (ICCDU), Aachen, Germany	JK	25/06/2019
Update report from IEAGHG	ADB Deep Dive Workshop, Manila, The Phillippines	JC	21/06/2019
CCS for Cement Kilns	CEMEX, Trondheim, Norway	MG	15/07/2019
An overview on the IEAGHG technical programme: CO_2 capture technologies for the power and industrial sectors, their integration and potential to reduce costs	CMTC-2019	MG	16/07/2019
Faults and their significance for large-scale CO_2 Storage Workshop	University of Calgary, Canada	JC	23/08/2019
International CCS Value Chain Developments – Global Context	NETL CCUS Review Meeting, Pittsburgh, USA	TD	29/08/2019
Biomasse mit Carbon Capture and Storage (BECCS/Bio-CCS) (in German)	8. Statuskonferenz Energetische Biomassenutzung, Leipzig, Germany	JK	17/09/2019
Understanding the cost of reducing water usage in coal and gas fired power plants with CCS	PCCC-5, Kyoto, Japan	MG	19/09/2019
Introduction to Effects of Plant Location on the Cost of CO_2 Capture	Webinar with Wood plc, online	KB	17/10/2019
The Global Scene for CCS	International Knowledge Sharing Symposium, Trinidad & Tobago	TD	29/10/2019
Update report from IEAGHG	CSLF Technical Group Annual Meeting, Chatou, France	TD	04/11/2019
The role of EIIs for the economic development of developed and emerging countries. Growth and geographical trends	CCUS and EIIs Workshop, Chatou, France	MG	05/11/2019
Carbon Removal and Return: Can CCS Decarbonise Industry in South America and Help the Oceans?	UNFCCC Side Event COP25, Madrid	TD	04/12/2019
Update on the London Protocol and CCS	CO_2 Capture Project's Survey of CO_2 Storage Regulations, IETA room, COP25, Madrid	TD	04/12/2019
Update report from IEAGHG	77th WPFF Meeting, IEA, Paris	KB	10-11/12/2019
Legal Developments to Enable CCS Clusters Update on the London Protocol and CCS	Transforming industry: Developing carbon capture, utilisation and storage clusters, UK Pavilion, COP25, Madrid	TD	11/12/2019
Sharing Learnings from Global CCS Developments and Projects	Saving Our Beautiful Planet with CCS (Part 2) Japan Pavilion, COP25, Madrid	TD	13/12/2019

Staff Abbreviations:

JC: James Craig
JK: Jasmin Kemper
KB: Keith Burnard
MG: Mónica García
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Table 6: List of 2019 IEAGHG Presentations continued

Members of the Programme

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Mr Lincoln Paterson (M) Dr Kelly Thambimuthu (Chairman)

AUSTRIA

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

CANADA

Dr Eddy Chui (M)

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Dr Vassilios Kougionas (M) Jeroen Schuppers (A)
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Dr Atul Kumar (M)

JAPAN

Mr Ryozo Tanaka (M) Dr. Ziqui Xue (A)

KOREA

Jeom-In Baek (M)

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Mr Mark Pickup (M)

NETHERLANDS

Gerdi Breembroek(M)

NORWAY

Dr Åse Slagtern (VC) Mr Hans Jorg Vinje (M)

OPEC

Mr Moufid Benmerabet (M) Dr Eleni Kaditi (A)

SOUTH AFRICA

Evelyyn Nyandoro (M)

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Mr Arthur Lee (M)

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Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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