Technology Collaboration Programme

by iea

ghgt-15

GHGT-15 Conference

15 - 18 March 2021

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 – twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 30 member countries and beyond. Within its mandate, the IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics. To date, there are 38 TCPs who carry out a wide range of activities on energy technology and related issues.

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

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

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

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

Or by telephoning the office on:

+44 1242 802911

Disclaimer

Document designed by Tom Billcliff.

Contents

GHGT-15 Conference Background

At the close of the previous GHGT conference in 2018, there was a clear intention to hold GHGT-15 in 2020 at Khalifa University, a vibrant and modern institution in the United Arab Emirates (UAE). It would have been the first time that a GHGT conference was held in the Middle East.

Regrettably, the COVID-19 pandemic meant firstly delaying the conference, and then running it as a virtual event. Despite the lack of social interaction and entertainment that GHGT conferences are renown for, delegates experienced a highly successful virtual event with seven parallel sessions. With excellent audio visual facilities, delegates could not only view but also participate in question and answer sessions following each recorded presentation. Live panel discussions provided added credence to the conference.

GHGT-15 was opened by His Excellency Eng. Awaidha Murshed Al Marar, Chairman of Abu Dhabi Department of Energy. His Excellency stressed the significant role that CCUS will play in the responsible energy transition for the UAE. Dr Arif Sultan Al Hammadi, Executive Vice President of Khalifa University, and GHGT Co-chair, added his welcome, noting that this was the first ever GHGT conference in the Middle East.

About the host

After four decades of remarkable growth and development, the UAE is now the nexus between west and east, the developed and developing, and the present and the future, and it is the meeting point between ancient and modern. In the UAE futuristic cities live hand in hand with ancient treasures. The wealth created by the UAE's natural resources now funds some of our world's most promising new green technologies.

Khalifa University of Science and Technology is an internationally top-ranked research-intensive university located in Abu Dhabi, UAE. It boasts three colleges, three research institutes, 18 research centres, and 36 departments covering a broad range of disciplines in science, engineering, and medicine. Khalifa University is the one university in the UAE with the research and academic programmes that address the entire range of strategic, scientific and industrial challenges of the 21st century.

Khalifa University is directly engaged in the development of CCS in a region still heavily dependent on oil and gas. The institution is a key part of Abu Dhabi's and the UAE's rapidly developing knowledge economy, which is actively seeking to decarbonize. For example, the country hosts the world's first carbon capture from a steel plant. The Emirates Steel Industries plant now captures around 0.8 million tons of CO_2 per year, which is supplied to ADNOC's onshore Al Rumaitha and Bab fields for enhanced oil recovery (EOR) via a 43 km (27 mile) pipeline.

GHGT-15 Statistics & Images

141
Reviewers

326
Oral Presentations

6 Technical Plenaries

3 Sponsor Speakers

3
Keynote Speakers

956
Delegates

186
Poster Presentations

774
Abstracts Received

6
Panel Discussions

71 Technical Sessions

GHGT-15 Steering Committee

CO-CHAIR
Dr. Arif Al Hamadi

CO-CHAIR
Tim Dixon

Dr. Ahmed Al Shoabi

Dr. Mohammad Abu Zahra

Dr. Fawzi Banat

Mrs Khulood Al Ali

Sayed Al Hashmi

Ahmed Al Azawi

Suzanne Killick

The GHGT-15 Conference series is organised by the Steering Committee, a group made up from members of the host organisation (Khalifa University) with support from the GHGT conference guardians (IEAGHG).

The Steering Committee is chaired jointly by Dr. Arif Al Hamadi of Khalifa University and Mr Tim Dixon of IEAGHG, and under their leadership the committee arrange the conference assisted by the Technical Programme Committee (TPC) to formulate the technical programme content, and overall structure of the event.

The opening of the GHGT-15 conference.

Setting the Scene: Key Points from Plenary Sessions

Keynote Addresses

Three distinguished guests lined up to give the keynote addresses that kick-started the high quality technical content of GHGT-15.


Mechtild Wörsdörfer

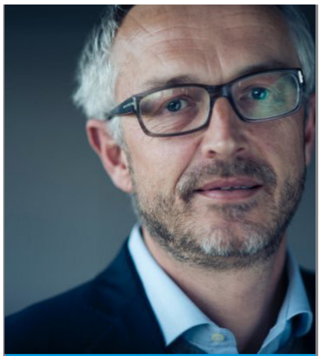
Mechtild Wörsdörfer, the IEA's Director of Sustainability, Technology and Outlooks, began by recognising the IEA Greenhouse Gas R&D Programme (IEAGHG) as a leading global source of objective information on CCS technologies and, as one of its Technology Collaboration Programmes, a valued member of the IEA's broader energy network.

Introducing her presentation on "CCUS in energy transitions", Ms Wörsdörfer observed that there had been many positive developments in the technology since GHGT-14 in October 2018. With major economies, along with many leading companies, committing to net-zero emissions by 2050-2060, CCUS would have a critical role to play in the decades to come. Since early 2020, she said that more than $8 billion had been committed to the development and commercialisation of CCUS, with initiatives from the likes of Bill Gates and Elon Musk raising its profile. In the September 2020 publication of its Special Report: "CCUS in Clean Energy Transitions", the IEA had shone a particular light on the technology. Significantly, the pandemic and consequent economic crisis saw global CO_2 emissions fall by 6% through 2020 – only for them to rebound by the end of the year to levels higher than they were one year earlier. To address this unwelcome trajectory, the IEA has called for CCUS and other clean energy technologies to be at the heart of governments' recovery packages.

Analysis shows that CCUS will have a major role in meeting the Paris goals, reducing emissions not just in power but also in transport, industry and buildings – contributing to 15% of cumulative CO_2 reductions to 2070. Ms Wörsdörfer addressed the IEA's four strategic roles for CCUS, and the role of carbon dioxide removal technologies, before wrapping up with four priorities for governments and industry to accelerate CCUS deployment over the next decade:

- Create the conditions to stimulate investment into CCUS. Investment in CCUS needed by 2030 is an estimated tenfold increase over the investment made during the decade to 2020.
- Target the development of industrial hubs with shared CO_2 infrastructure. This could play a critical role in accelerating the scale-up of CCUS by exploiting economies of scale and making it feasible to capture CO_2 at smaller industrial facilities.
- Identify and encourage the development of CO_2 storage. Confidence in the availability of safe, secure and adequate CO_2 storage is a prerequisite for investment in both transport and storage infrastructure and capture facilities.
- Boost innovation for critical CCUS technologies. Innovation will be key to scaling up CCUS in both the short and long term.

OGCI, whose 12 oil and gas (O&G) member companies produce more than 30% of global O&G output, was created to accelerate the industry's response to climate change. **Bjørn Otto Sverdrup**, Chair of OGCI's Executive Committee, presented "OGCI's Role in Accelerating Deployment of CCUS at Scale". OGCI, he said, has created a $1 billion venture fund to drive investment in low-carbon technology and, for many positive reasons, for example, its potential to address hard-to-decarbonise areas and to produce low-carbon cement and steel, CCUS is one of its priority areas.



Bjørn Otto Sverdrup

With momentum picking up as more countries are signing up to a net-zero target by mid-century, CO_2 storage will need to transition from today's 10s of Mt/year to Gt/year. For this to happen, Dr Sverdrup pointed out, safe, permanent and environmentally responsible storage options will be required. As a resource, OGCI has developed (with GCCSI) a practical CO_2 Storage Resource Catalogue, updated annually and published on OGCI's website.

While CCUS was often perceived as a cost burden, it is actually about creating value and jobs while decarbonising the economy, opening up multiple opportunities in multiple regions. To realise this ambition, he stressed that business models must be developed and effective policy frameworks put in place; and OGCI was in discussion with the CEM CCUS initiative to progress these vital actions. Having investigated 26 countries with a view to matching emission sources with CO_2 storage sites (using its CO_2 Storage Resource Catalogue), OGCI had identified over 100 potential CCUS hubs, with 15-25 of them showing good potential for development. OGCI is providing a kick-start to eight of these CCUS hubs, of which four are on track to be operational by 2025.

Dr Sverdrup went on to describe some of OGCI's regional studies. One, looking at the huge potential for CCUS in Saudi Arabia and other GCC states, was to be published shortly; with another study, on China, presently underway. Concluding his talk, he said that 2021 would be a crucial year both to demonstrate climate action and to demonstrate renewed collaboration on CCUS.

Roy Vardheim, Acting CEO of Gassnova, described an important climate initiative in his keynote presentation entitled, "Longship – Creating Value Chains for CCS in Europe". It was on 21st January 2021 that the Norwegian government voted to launch the first full-scale value chain – capture, transport and storage – ultimately to safely and securely store CO_2 under the North Sea. CCS, he said, is widely recognised as an essential technology, one that must be widely deployed if the targets of the Paris Agreement are to be met. Demonstration at scale will be a major factor in bringing down the costs of the technology, making it less expensive for application in many industry sectors. In the long run, to reach net-zero emissions, negative emissions will be needed and CCS will be key to achieving that goal as well.

Roy Vardheim

Mr Valdheim reminded listeners that Norway has been in the vanguard of European CCS development over many years, a long storyline that began when Norway imposed a carbon tax in 1991. For example, in the Sleipner project, CO_2 separated from natural gas has been stored in a saline aquifer under the North Sea over the past 20 years – over 20 million tonnes stored and counting; and Technology Centre Mongstad, a globally renowned capture test facility, has been in continuous operation since 2012.

For the Longship project, one capture facility (Heidelberg cement plant at Brevik) is being fully funded by the Norwegian government, with a second (Oslo's Klemetsrud waste-to-energy plant) conditional upon co-funding from other sources. The CO_2 transport (by ship and pipeline) and storage operation is being run by the Northern Lights consortium comprising Equinor, Shell and Total. A major attribute of Longship is that, as interest in the project grows, the storage capacity can be expanded to store CO_2 captured from other facilities, and not only from Norway but also from elsewhere in Europe. Dr Vardheim acknowledged the active and constructive role of IEAGHG in the important decision taken under the London Protocol to permit cross-border transport of CO_2 across borders.

He explained how a new business model had been successfully developed to enable the project to proceed. An important element and, in fact, a firm requirement of State funding was that experiences and knowledge should be shared with government bodies, Industry and others. The first volume covering lessons learned has already published and may be accessed via https://gassnova.no/wp-content/uploads/2020/11/Gassnova-Developing-Longship-FINAL-1.pdf.

Technnical Plenary: US FEED and Carbon Safe Projects - Presented by Dr Jennifer Wilcox, Principal Deputy Assistant Secretary for Fossil Energy, US DOE

Prior to entering the Biden-Harris administration, **Dr Jennifer Wilcox**, Principal Deputy Assistant Secretary for Fossil Energy, US DOE, was a distinguished professor at the University of Pennsylvania and Senior Fellow at the World Resources Institute. With an accomplished background in direct air capture technologies, she has published extensively. Dr Wilcox is well known as an ambassador, promoting greater female representation in the sciences. She is also a great friend of IEAGHG, having lectured and mentored students on two IEAGHG CCUS Summer Schools, as well as having been a panellist at an IEAGHG organised side-event at COP25.

Climate change, she said, has become a climate crisis with little time left to address the worst impacts of climate change, its threat to public health, communities and the economy, and even to our ability to live on planet earth. There had been a growing response by many nations, many cities and corporations to meet net-zero GHG emissions by mid-century. Dr Wilcox said that, if done thoughtfully and strategically, the transition to net zero will not only tackle climate challenges but provide more and better quality jobs, and maybe even economic benefits that exceed the costs.


Dr Jennifer Wilcox

Rising to these challenges and seizing the opportunities presented was one of the goals of the Biden-Harris administration, with its mission to achieve a clean energy economy and net-zero emissions by mid-century. However, she noted that it was a global crisis and not one that a single nation or group of nations could respond to alone. Cooperation and collaboration was required, with a common commitment to achieve common goals – hence the decision for the United States to rejoin the Paris Accord.

Fossil fuels, she said, need to be decarbonised where they are difficult to displace with non-fossil options. To achieve this, we need to accelerate the deployment of existing technologies, with CCS indispensable to that effort. While the deployment of CCS has been slow, good progress had been made over the past decade. There were now around 65 CCS projects at various stages of development worldwide, a 33% increase since 2019. The United States has long been at the forefront of developing and deploying CCS, but much more effort is required globally in this space. However, challenges remain, most notably a shortage of policy to make the technology economically viable.

With the upturn in deployment, 'learning by doing' was driving down the costs of CCS. US DOE-funded projects were currently storing around 23 Mt CO_2. Dr Wilcox described the CarbonSAFE Initiative, where projects are focusing on the development of geological storage sites for storing over 50 Mt CO_2 from industrial sources.

Dr Wilcox tellingly stated that CCS needed to be taken out of its silo. The technology was not a theoretical concept. Many commercial-scale options were available today. There must be a focus on low-carbon products, such as low-carbon cement, concrete, paper, fuels, chemicals, plastics, etc. For example, CO_2 and clean hydrogen can be used to produce synthetic chemicals and fuels. At the Port Arthur refinery, hydrogen produced from a steam methane reformation (SMR) facility had led to the separation and safe geological storage of 6 Mt CO_2 to date.

Collaboration was required across government academia and industry, and across international borders. More and more companies were embracing reality that they need to reduce carbon emissions in their industry. It was recognised that, to achieve net-zero, carbon removal from the atmosphere will be important, mainly due to the hard-to-decarbonise sectors, for example aviation and agriculture. Yet, she said, it would always be the cheaper and easier option if carbon emissions could be avoided to begin with – less carbon emissions, less to manage.

Emphasising the Biden-Harris administration's commitment to addressing the climate emergency, Dr Wilcox pointed to the many other emission reduction pathways supported by the US DOE, including those of the advanced turbines programme, the fuel cells programme, and the numerous initiatives undertaken by its O&G office.

Technnical Plenary: ADNOC Phase 2 Project - Presented by Mr Ahmed Bin Amro ADNOC

Ahmed Bin Amro

As Vice President – Enhanced Oil Recovery at ADNOC, **Mr Ahmed Bin Amro** oversees all ADNOC's onshore and offshore reservoir EOR activities. For his presentation, Mr Bin Amro shared ADNOC's efforts and commitments regarding sustainability as the company moves towards 2030.

Global warming and climate change must be addressed, with the effort to tackle GHG emissions by deploying CCS a critical and important subject. CCS has a key role to play in a climate-friendly future energy scenario by integrating clean energy with traditional energy. ADNOC, he said, was an advanced national oil company and, with its world-class hydrocarbon sources base, the largest contributor to the UAE economy.

Mr Bin Amro said that ADNOC planned to build on its legacy as a responsible O&G producer to become best-in-class in sustainability and, in doing so, maximising value for the UAE. With the UAE having signed the Paris Agreement, ADNOC would continue to pursue and implement policies to reduce GHG emissions. He introduced ADNOC's Sustainability Strategy, with its six sustainability pillars.

Starting with its Climate Emission and Energy Pillar, ADNOC aimed to become the leading O&G operation in emission management and energy efficiency, minimising impact on the local environment. Under this pillar, he said, ADNOC planned to decrease its GHG emissions intensity by 25% by 2030, with CCUS capacity expanded from the current 800,000 t CO_2/year to over 5Mt/year before the end of the decade. There were several drivers for ADNOC's CCUS strategy. Its carbon footprint would be reduced while still contributing to global energy demand. Where commercially viable, 70% field recovery would be achieved through the application of advanced and innovative EOR techniques. Natural gas would also be liberated to serve the growing demand for energy. CCUS would be instrumental in achieving these aims.

Mr Bin Amro described UAE's Al Reyadah plant, the world's first commercial capture from the iron & steel industry. Beginning operation in 2016, the plant captures 800,000 t CO_2/year, which is exported via a 43 km buried pipeline and used for EOR in two of ADNOC's oilfields. He then went on to discuss ADNOC's CCUS roadmap and plans to expand capture to >5 Mt CO_2 by end of decade –equivalent to the capture capacity of over 5 million acres of forest, which would require an area twice the size of the whole UAE. Detailing how ADNOC plans to achieve its CCUS targets, he highlighted that ADNOC's Shah gas plant has the potential to enable capture of 2.3 Mt CO_2 while its Habshan and Bab plant could enable the capture of almost 1.9 Mt CO_2. ADNOC's priorities would focus on cost reduction and the development of low-cost CO_2 capture, and on innovative solutions to realise the full CCUS value chain.

In wrapping up, Mr Bin Amro said that ADNOC would continue to make global climate change mitigation the highest priority in its long-standing commitment to environmental stewardship.

Technnical Plenary: Hydrogen and CCS - Presented by Dr Motohiko Nishimura, Vice Executive Officer of Kawasaki Heavy Industries

Dr Motohiko Nishimura opened his address by highlighting the advantages that a hydrogen based economy can offer. Firstly, an energy system exclusively based on renewables and battery storage is limited by energy scale, facility cost and applications. Liquified hydrogen enables long-distance, long-term transportation, energy storage and connects with multiple sectors. Moreover, a wide range of industries are involved in the supply chain and demand fields. Hydrogen now has worldwide relevance to a versatile cycle for the global environment and economy.

Dr Motohiko Nishimura

Kawasaki Heavy Industries directly contributes to decarbonisation because it is the only company that owns and operates the entire hydrogen supply chain from production, transportation, storage and utilization.

Kawasaki is working with a number of partners on a pilot project supported by the Japanese and Australian Governments. The company is supplying the gasification and hydrogen production plant at the Loy-Yang A Brown Coal Power plant in the Latrobe Valley, Victoria. A sea tanker fitted with a 1,250 m^3 liquid hydrogen tank, was launched on 11th December 2019, as part of this joint pilot project. The vessel has a diesel-electric propulsion system capable of 13 knots (6.61 m/sec). A liquefied hydrogen storage and loading system capable of holding 2,500m^3 is now installed in the port of Kobe. These pilot scale facilities are a prelude to commercial scale operations with 40,000 m3 capacity sea tankers delivering liquefied hydrogen to receiving tanks with 50,000m3 capacity.

Kawasaki is developing, in partnership with Obayashi, Kobe City, KEPCO (Korea Electric Power Corporation), Iwatani, Kenes and Osaka University, a pilot 1 MW CHP turbine using pure hydrogen, natural gas and a mixture of these fuels. The system can deliver approximately 1,100 kWe and 2,800 kWTH. Heat and power are being supplied to an urban area using this hydrogen fueled system which was first achieved in April 2018. In addition, Kawasaki are involved in a high efficiency capture plant capable of 40 t CO_2 / day. It will be demonstrated at the Malzuru coal fired power plant in Kyoto Prefecture. DAC is also being developed in a project initiated in 2019.

These developments collectively demonstrate Kawasaki's commitment to the development of the hydrogen economy especially in Japan.

Technnical Plenary: Global Cement and Concrete Association (GCCA) - Presented by GCCA Cement Director, Claude Lorea

Claude Lorea noted that the GCCA has a climate ambition, committing to continuing 'to drive down the CO_2 footprint of their operations and products, and aspire to deliver society with carbon neutral concrete by 2050. The GCCA will work across the built environment value chain to deliver this aspiration in a circular economy, whole life context'.

Claude Lorea

Concrete is essential in the modern world. Population growth and increasing urbanisation will drive a growing global requirement for critical infrastructure in the future. There is a growing need for resilient construction to protect our cities and the natural environment from the effects of climate change. Concrete is essential to meeting these challenges and sustainable development. Concrete is the world's leading sustainable building material and has many performance benefits.

Producing cement is energy intensive and its process emissions account for 60% of total CO_2 emissions. The cement industry has already made important progress in reducing these emissions. Since 1990, a reduction of 19.2% has been made in CO_2 emissions per tonne of cementitious material and a nine-fold increase in alternative fuel use replacing conventional fossil fuels. In the coming decade the GCCA can provide society with carbon neutral concrete, by a number of methods including co-processing of waste from other industries, biomass, using renewable electricity sources, carbon capture and recarbonation. CCS will be needed to achieve the goals and there are already a large number of cement industry carbon capture and carbon use projects across the world.

GCCA is driving industry sustainability in its low carbon built environment roadmap for the route to 2050. They have also recently launched 'Innovandi', the Global Cement and Concrete Research Network to foster innovation and explore opportunities for the future.

Technnical Plenary: China and CCS updates - Presented by Dr Xu Shisen, China Huaneng Group Clean Energy Research Institute

With an installed capacity of around 200 GW, the China Huaneng Group (CHNG) is the largest power group in China and, in fact, in the world. **Dr. Xu Shisen**, who briefed attendees on some of China's extensive range of CCUS-related activities, past and present, is Chairman of CHNG's Clean Energy Research Institute.

Dr Xu Sishen

Dr. Xu began by reminding listeners of President Xi's recent announcement that China will aim to hit peak emissions before 2030 and achieve carbon neutrality by 2060. To achieve these ambitious and challenging targets, it is recognised that CCUS, together with a range of other technologies, will make an essential contribution in China.

Today, Dr. Xu said, there were some 25 CCUS projects operating in China, deploying the full range of capture technologies – pre-combustion, post-combustion and oxy-combustion. Many of China's leading power utilities and O&G companies were now engaged to greater or lesser degrees in CCUS activities. Apart from the China Huaneng Group (CHNG), others engaged in various aspects of CCUS include the China Energy Investment Corporation with its focus on storage, and the O&G companies Sinopec, Petrochem and Yangchang Petroleum International with their efforts on storage and EOR.

Dr. Xu went on to describe in a little more detail some of the highlights in CHNG's embrace of CCUS, which encompasses R&D, pilot-scale testing and demonstration. At CERI and its various pilot and demonstration facilities, he said, CHNG is engaged in system integration and the development of various capture technologies, including slurry-based absorbents and biphasic solvents. At larger scale, however, China has continued to make important headway.

In 2008, the first demonstration of post-combustion capture was demonstrated on a side-stream from a coal-fired cogeneration plant located in Beijing. Capturing 3,000 t/year, the CO_2 was used in the food and drinks industry.

In 2009, the design was scaled up to 120,000 t/year at the Shidongkou coal-fired plant in Shanghai. Operating at a capture rate of 85%, with an energy consumption of 2.7 GJ/t CO_2, this was the largest operating CCS facility in the world until 2014.

In 2013, post-combustion capture was demonstrated on a gas-fired pilot plant in Beijing, capturing 1,000 t/year CO_2.

In 2016, this was followed up with the demonstration of pre-combustion capture on a 30 MWth IGCC plant at Tianjin. Up to 100,000 t/year was captured at the plant, with an energy consumption of < 2.3 GJ/t.

CHNG is a board member of the China Technology Strategic Alliance for CO_2 Capture, Utilization and Storage Technology Innovation (CTSA-CCUS). Its membership includes the major power and O&G companies and academia, with state involvement via the Ministry of Science and Technology and the Ministry of Ecology and Environment. The CTSA-CCUS acts as a major body for both domestic and international cooperation, involving cooperation with Japan, the United States, Korea and Australia, amongst others.

Dr. Xu said that China's plans to continue its focus on CCUS, including further work on post-combustion and pre-combustion capture, EOR and aquifer storage, and on large-scale demonstration

Technnical Plenary: Oxy DAC project - Presented by Dr Robert Zeller, Oxy VP Technology of Oxy Low Carbon Ventures

Dr Robert Zeller, VP Technology of Oxy Low Carbon Ventures, presented an update on the DAC-1 project in the Permian basin. For this, Oxy can rely on their 40+ years of experience in building carbon sequestration infrastructure in the region. The DAC-1 project will consist of a single train capturing 1 Mt CO_2/year (removing 500 kt CO_2/year from the atmosphere) and is expected to start operating in 2025. Oxy acquired a license from Carbon Engineering to use their DAC technology, for which Worley will deliver the FEED (front-end engineering design) study by the end of 2021.


Robert Zeller

DAC should be seen as an alternative to point-source capture – when and where it makes sense. Drawing on the higher degree of freedom of DAC plant locations compared to point sources, they could be ideally co-located with the best available CO_2 storage reservoirs. Dr Zeller highlighted that establishing carbon removal as a service could be a lifeline for industries with limited mitigation options.

Policy & Regulation

In GHGT-15's session on Policy International and Incentives, some significant work was shared on CCS and the Sustainable Development Goals (SDGs), undertaken by TNO for IEAGHG and also by Imperial College on CCS in 'Just Transitions'. This work is helping to identify and fill data gaps for CCS and stimulated much discussion. It was noted that such evaluations undertaken by IPCC should not be done in isolation on only one technology, but should be done across all mitigation technologies with a fair comparison. The Life Cycle Analysis (LCA) work to date that is used by IPCC on CCS has focussed on coal power generation and not gas power, thus misrepresenting the environmental impacts for CCS on gas power. The benefits to SDG-8 with employment from CCS were noted to contribute to the 'Just Transition' cause. Also covered in this session was work on future financing models and needs for future CCS deployment, from Carbon Limits, and work on potential incentives for CCUS in China by NICE.

In other sessions, attendees also heard updates on national CCUS policies and activities in Trinidad and Tobago and in Mexico, important developing countries for CCUS. An important aspect to certainly European projects is financial security for long term liability.

In the regulatory session, attendees heard from TNO and partners who have estimated the financial security needed for their estimates of leakage risks under the EU's CCS Directive, concluding that this should be proportional to the actual risk and therefore much smaller than some initial assumptions (including in the EU Guidance Document 4). The University of Texas presented on monitoring for long-term post-injection monitoring for 100 years required under the Californian Low Carbon Fuel Standard, the challenges and also feasibility of meeting this requirement. IEAGHG and the IMO (International Maritime Organisation) presented on the resolution to the London Protocol's export prohibition on CO_2, removing the last significant international legal barrier to widespread CCS deployment.

Key Policy and Regulatory messages overall

Some strong incentive policies now exist for CCUS, for example 45Q in the US and the Californian Low Carbon Fuel Standard, and a recurring theme in this conference was how to meet the requirements of these existing incentives for real projects, as well as analyses on options for new incentive policies for other countries. The UN's Sustainable Development Goals are being increasingly used when considering climate action, and this conference shared advances in filling in the knowledge gaps for CCS in this area. Also, this conference saw a significant advancement in removing the remaining legal barriers to widespread deployment of CCS.

IEAGHG General Manager Tim Dixon discusses the session on Policy - International and Incentives with speaker Israel De Araujo, Postgraduate Visiting Research, Imperial College London

CCS Deployment

One of the most significant advances in deployment is the intention of the Norwegian Government to support the Northern Lights project which will be the first full-chain source to sink demonstration project. During GHGT-15 there were a number of other projects and plans to develop CO_2 hub projects in the USA, UK, and the Netherlands with real prospects for development within the next decade. As large-scale CCS projects become a reality and increase in number one of the most important aspects of deployment will be public acceptance. One of the challenges is trying to convey the impact of CCS prior to the establishment of a project. A team from CSIRO have trailed a virtual reality experiment to test whether the technique might help future communities gain a realistic impression of the technology's impact. The team approached delegates during GHGT-14 to gauge their reaction. Participants were guided initially through 2D impressions and then 3D images. The tour was based on an actual CCS project in Australia from capture site to storage location. Given the composition of the audience many people had never considered what a whole CCS chain might look like especially the subsurface. There was a recognition that community engagement is vital and requires an ambassador to convey the benefits as well as the impacts.

Outreach actvities were explained in a talk from a representative of the Japan CCS Company on the Tomakomai project on Hokkaido. The objective of the company's outreach programme was to ensure that local stakeholders in the city understood the CCS project and that they were reassured about safety and security. A series of communication activities have been conducted since the inception of the project to establish trust and nurture a positive relationship. Significantly the outreach programme was designed from the local stakeholders' perspective. A series of activities including publications, lectures and bus tours have been used and aimed at different age groups. The Programme has also been proactive when, for example, there was a large natural earthquake, the outreach team were quick to demonstrate that there was no evidence of leakage from the injection site. They also conducted a bus tour one month after the natural seismic event and held a public forum that was attended by almost 400 people. Japan CCS Company would like to extend their outreach experience to other projects and organisations to overcome common issues and barriers.

Research and Development Achievements – Key Highlights

- **The Gorgon Project, Australia** is one of the world's largest natural gas projects and this commercial-scale CCS demonstration project started the injection of CO_2 in 2019. So far, the storage project has seen good injectivity overall and to date, over 4 million tonnes of CO_2 has been injected.
- **Northern Lights Project, Norway.** One of the most significant advances in deployment is the intention of the Norwegian Government to support the Northern Lights project which will be the first full-chain source to sink demonstration project. During GHGT-15 there were a number of other projects and plans to develop CO_2 hub projects in the USA, UK, and the Netherlands with real prospects for development within the next decade.
- **Wyoming CarbonSAFE**: This CarbonSAFE project, funded by the US DOE, aims to ensure carbon storage complexes will be ready for integrated CCUS system deployment, with Phase 3 of the project launched in October 2020.
- **Port Arthur SMR retrofit, Texas, USA** which has captured more than 6 Million Tonnes to date. This project includes the retrofit of 2 SMRs (stream methane reformers) included in a refinery.
- **Amine emissions** are no longer the problem they once were, though some effort was still needed on amine oxidation. Challenges remaining included the capital cost, which needs to come down, and the realisation that 99+% efficiency was now the target. Second generation amines were presently hard to beat.

- **Kawasaki** is working with a number of partners on a pilot project supported by the **Japanese and Australian Governments**. The company is supplying the gasification and hydrogen production plant at the Loy-Yang A Brown Coal Power plant in the Latrobe Valley, Victoria. A sea tanker fitted with a 1,250 m3 liquid hydrogen tank, was launched on 11th December 2019, as part of this joint pilot project. A liquefied hydrogen storage and loading system capable of holding 2,500m3 is now installed in the port of Kobe. These pilot scale facilities are a prelude to commercial scale operations.
- Even without applying CCS, the **WtE (waste-to-energy) sector** has already achieved emissions reductions. When applying CCS, about an additional tCO_2eq/t_{waste} can be saved. Under the right conditions, biogenic waste could become a strategic resource for achieving negative emissions, without the impacts on food security/land availability that other BECCS pathways might have.

Post-Combustion Capture

During GHGT-15 there were a number of examples of prospective solvents which could be used in post-combustion capture. The solvent compositions ranged from amines, to ammonia and alkali salts and in one case a molten alkali metal borate. The research and development of these solvents has the aim of reducing capture cost, improving solvent durability and reducing energy demand especially specific reboiler duty. Examples of another concept, cryogenic capture, was also covered.

Highlights from the post-combustion capture session included:

- Pilot plant results with the Piperazine (PZ) Advanced Stripper (PZAS) at NGCC (natural gas combined-cycle) conditions.
- The results of an 18 month test with aqueous AMP (Ternary 2– Amino– 2– methyl– 1– propanol)/PZ solvent at a pilot plant at Niederaussem. Evidence from long-term (>12,000 hours of operation) showed that at a 90% capture rate minimum specific reboiler duty (SRD) of 2,970 MJ/tCO_2 was achieved. A low degradation rate and linear degradation behaviour was also observed, however more investigation on emissions countermeasures is required.
- Examples of using cryogenic capture at pilot scale suggested promising results in terms of estimated costs of CO_2 capture, energy demands and ease of retrofit. Multipollutant capture, energy storage, water capture from flue gas and ease of integration also offer benefits. Tests are being conducted at a cement plant; and another at a coal-fired power plant in the United States. Another unit is scheduled for deployment at the REBEC heavy fuel oil power plant near Rabigh, Saudi Arabia.
- In another study a cryogenic capture technique at a site in Normandy has improved efficiency and has lowered emissions compared with amine capture. Costs as low as 30€/tonne for CO_2 captured were claimed.
- In contrast to amine based or cryogenic technology, a less advanced concept was presented based on molten alkali metal borates for high-temperature carbon capture. This process uses a molten salt in the form of a metal oxide, sodium borate, which is liquid at 600°C. The advantage of using this medium is that it enables capture within a liquid to liquid phase. This condition avoids sintering and allows rapid reform and regeneration over many cycles. The estimated cost of CO_2 avoided using this technology is $34/tonne but there is a wide uncertainty range $18 - $56/tonne.
- Another capture technology based on a mixed-salt (potassium carbonate and ammonium salts) process (MSP) was presented. Development began in 2004 at lab scale and has now advanced to a pilot project to be trailed at a field testing site in Illinois. The current plan is integration of MSP testing for prolonged periods under dynamic and continuous steady-state conditions with a real flue gas stream.

Hydrogen & CCS from Industrial Sources

This session showed the international interest on hydrogen production. Speakers presented the different phases of the development process, including experiments at lab scale, implementation at large scale, and the importance of low carbon hydrogen in collaborative decarbonisation objectives.

- Roger Dewing, from Air Products plc, discussed the retrofitting of existing SMRs (Steam Methane Reformer) with CO_2 capture. He presented the Port Arthur SMR retrofit, which has captured more than 6 Million Tonnes to date. This project includes the retrofit of 2 SMRs included in a refinery. The project captures the 90% of the CO_2 contained in the syngas, and the captured CO_2 (56,000 Nm3/h) is used for EOR (Enhanced Oil Recovery). The CO_2 capture system is based on a developed in-house CO_2 capture technology, which includes a VSA (Vacuum Swing adsorption) with standard solid absorbents, tested previously at pilot scale. Future applications are expected in the Porthos Project (Netherlands) and other existing SMRs.
- Gunhild Reigstad, from SINTEF Energy Research, presented the ELEGANCY project. This project addressed the H2 supply chain, assessed the business cases, and explored the social and environmental aspects. Different case studies in various countries were investigated (United Kingdom, Switzerland, Norway, Netherlands, and Germany). These explored the impact of decarbonised hydrogen in different sectors, such as transport and energy, and how these are integrated in industrial clusters.
- Rahul Anantharaman, from SINTEF Energy Research, presented the efficient low carbon hydrogen production from natural gas. The approach analysed the difference between the maximum theoretical efficiency and the state-of-the-art efficiency, and later implementation of a systematic methodology called "G-H". The process design, which included membrane reactors, minimised losses by operating close to reversible conditions.
- Espen Steinseth Hamborg, from Equinor Asa, presented the Norwegian hydrogen value chain demonstration (HyDemo), which fits in the Equinor's climate roadmap towards 2050. In terms of the capture technology, the team is still looking for the best available systems from technical and economic perspectives. Equinor's Low Carbon Project Portfolio includes operations which have been successfully operated on their applications in different sectors since 1996.
- Anne Streb, from ETH Zurich, presented the experimental set-up and implementation of a VPSA (vacuum pressure swing adsorption) cycle. This technology is at a technology readiness level (TRL) 4 and is a potentially promising alterative for coupling H2 production with CCS. The results showed changes on the CO_2 and H2 purity through modifications on the process configuration. Furthermore, the simulation model had a good agreement with the experiments.

CCS development with industrial sources covered a number of sectors with high CO_2 emissions. Fertilisers, cement, iron and steel featured in the conference programme as well as examples of plans to link industrial conglomerates into hubs.

- Fertiliser manufacturing can now produce a nearly pure CO_2 steam as part of the ammonia production process. The lowest cost case is now ~US$57.5/t CO_2. Capture of an additional 33% from reformer flue gas can account for an increase of LCOC (levelised cost of carbon) of 41% but achieves ~95% CO_2 from overall plant. The detrimental effect of NOx on carbon capture solvent needs to be monitored and addressed.
- Cement plant specific cost is much higher (~US$154/t CO_2) compared to fertiliser plant (~US$81/t CO_2). Retrofitting capture plant is likely to be more expensive than fitting such a facility to a new cement plant.

- For any current or future CO_2 capture project proper flue gas characterisation is of key importance as components can significantly impact amine emissions, solvent degradation and material compatibility.
- Operational experience from Technology Centre Mongstad (TCM) with RFCC (retrofitted carbon capture) and CCGT (combined-cycle gas turbine) flue gas can be used directly for any CO_2 intensive industries capture project.
- Stringent solvent management means efficient operation, reduced amine loss and fewer shutdowns and therefore increased chance of meeting emission reduction targets.
- Six sectors cement, silicon / ferrosilicon, ferromanganese, lime, aluminium and steel reinforcement have been investigated in a single project covering central Norway. It investigated different products and markets, CO_2 per unit produced, market price vs capture cost, off-gas qualities, energy mix and process topology. Absorption technology and membrane technology cases were investigated. CO_2 capture will be a part of future development within several sectors. Ship transport will be an important CCS enabler given the widespread distribution of these industries across Norway. Formation of regional hubs and cluster will be essential for project development.
- Near-zero CCGT's and steam methane reformers (combined fuel and power), with shared multiple infrastructure requirements, have been proposed including post-combustion carbon capture plant. Carbon neutral, on demand hydrogen and power are now considered to be economically feasible.
- Biomass supply for BECCS has been modelled for Sweden. A study has looked at biomass residue within 200 km of major paper and pulp producing centres to supply CCS heat. Biomass supply for heat generation may be a limiting factor for large-scale BECCS implementation depending on population density and the degree of demand from biomass fired district heating. CCS/BECCS should be planned in concert with inter-regional infrastructure for biomass supply and CO_2 transportation.

Geological storage of CO_2

- **Gorgon project, Australia:** The Gorgon project is one of the world's largest natural gas projects and this commercial-scale CCS demonstration project started the injection of CO_2 in 2019, aiming to store between 3.4 and 4 million tonnes per year. The CO_2 is captured directly from the gas field and then transported via pipeline to the injection site, the Dupuy saline aquifer, 2.3km beneath Barrow Island. So far, the storage project has seen good injectivity overall and to date, over 4 million tonnes of CO_2 has been injected. The first seismic survey will be undertaken later in 2021.

- **Tomakomai CCS Demonstration Project, Japan:** Since 2019, CO_2 has been injected into a sub-seabed formation and the operation of a full-chain CCS system – from capture to storage – has been successfully achieved. Monitoring operations are continuing at this project, where 300,000 tonnes have been successfully injected into the Moebutsu Formation. Importantly, there has been no microseismicity or natural earthquakes attributable to the injection programme. No CO_2 leakage has been detected in marine environmental surveys and the 2018 earthquake in the area did not cause any damage to facilities or storage reservoirs. There is no data linking CO_2 storage with this seismic event.

- **Otway Stage 3, Australia:** The third phase of this multi-stage storage programme, located in southwestern Victoria, is underway. Active monitoring methods are being tested at this site where injection is approaching 10,000 tonnes, including VSP (vertical seismic profiling) and pressure tomography, as well as passive methods such as microseismicity and earth tides. So far, the budgeting, handling and injecting of water for the pressure tomography has been challenging due to some minor system problems with injectivity, but the largely automated nature of acquisition and initial processing of seismic data has been a great triumph.

Early results show that the baseline data from the VSPs looks good, the pressure tomography has imaged the pre-injection distributions of porosity and diffusivity and there are preliminary time-lapse images from both modalities.

- **Salt water analogue for CO_2 storage, US Gulf Coast:** This work by ExxonMobil looks at the feasibility of large-scale CO_2 storage using salt water disposal data as an analogue. In the US, the produced water equivalent of 1 gigaton of CO_2 per year has been permanently disposed of for the last decade. Data shows that in the US Gulf Coast region alone, 1,500 currently active water disposal wells can inject the volume equivalent of more than 1 Gt CO_2/yr with an average injection rate of 20,000 bbl/day (0.8 MtCO_2/yr) per well. It is technically feasible to inject and store gigatons of CO_2 per year at the US national level and at the US Gulf Coast regional level; there is ample storage capacity and theoretical capacity in the study area.

- **CO_2-EOR at Farnsworth, Texas:** The US Department of Energy (DOE) is tasked with developing technologies to safely and permanently store CO_2 without adversely affecting energy use. A robust site geological model is central to each and every one of the carbon storage programme goals. Ongoing characterisation and monitoring methods at the Farnsworth site have afforded researchers the opportunity to validate technologies in near field laboratory conditions. Continuous updates in the geological model of the site have improved estimates of storage capacity and geometrical trapping through advanced seismic imaging and inversion; an understanding of petrophysical properties impacting CO_2 movement and capillary trapping by integration of core flow and petrogenic analyses; and estimates of key geomechanical properties impacting mechanical storage permanence through integration of specialised mechanical data analysis. The geological model is the primary framework within which researchers can benchmark the efficacy of these advancements, each of which contributes to the understanding of reservoir lithology, heterogeneity and geometry necessary for prediction of fluid flow, sweep efficiency, oil recovery and storage potential.

- **Wyoming CarbonSAFE:** The CarbonSAFE project is funded by the US DOE and aims to ensure carbon storage complexes will be ready for integrated CCUS system deployment, with Phase 3 of the project launched in October 2020. The end of project completion goals include carrying out 2D and 3D seismic, the environmental and risk assessments, MVA strategy, pore owner acquisition, economic and business models (among other goals) which will then help the project move towards commercial readiness. There will be two commercial injection wells; the first site is fully permitted and the methodology and data from this first site will be transferred to other sites to expedite the permitting. The wells will be under Class VI permitting regulations, very few of which have been permitted to date so this is a good indication of progress in the area of site permitting in the US particularly as projects move forward and will provide learning opportunities.

- **Decatur project, USA:** At the Illinois Basin – Deactur project, 1 million tonnes of supercritical CO_2 was injected in phase 1 from 2011 to 2014 into the Lower Mount Simon sandstone formation. The second phase, injection into a shallower part of the formation, has been ongoing since 2017. Recently, work has been completed by Norsar on a generalised and conceptualised microseismic model for the site. The microseismic events provide a continuous picture of stress changes within the reservoir, complementing active seismic snapshots. They observed the failure on consecutive fracture splays over time upon modification of stress conditions due to injection. Such a detailed characterisation of seismicity requires a sufficient monitoring programme in place with downhole sensors for improved detectability with high quality data and improved azimuthal coverage by additional surface sensors. This experience highlights the importance of microseismic monitoring for CCS; for reservoir monitoring and characterisation, and for risk assessment and mitigation.

- **Nagaoka site, Japan:** The Nagaoka injection site operated between 2003 and 2005, injecting 10,400 tonnes of CO_2 into a geological layer that was 12 metres thick at a depth of 1,100 metres. The work presented at this conference studied the relationship between Vp change and CO_2 saturation using time-lapse logging data at the Nagaoka site. Different relationships were observed in the data of limited depth intervals (due to lithofacies and CO_2 saturation at residual states) and it was observed that the relationship was different between drainage and the imbibition process. This demonstrates that the evaluation of the amount of CO_2 by seismic methods in the post-injection phase should be done carefully.

Negative Emissions

Several presentations investigated options to achieve net negative emissions. They included either BECCS (bionenergy with CCS) or DAC approaches.

BECCS

- Significant cost differences exist between regions, due to factors such as yield, labour cost, proximity of biomass supply to storage and wholesale electricity price. Storage appraisals and surveys will be crucial for delivering negative emissions, as storage availability can decrease total costs by up to 30%.
- Achieving negative emissions in urea production is possible but only by combining CCS with fuel switching to biofuel. The LCOU (levelised cost of urea production) will increase significantly compared to the base case, from 257 €/turea to 323 – 410 €/turea.
- Even without applying CCS, the WtE (waste-to-energy) sector has already achieved emissions reductions. When applying CCS, about an additional tCO_2eq/twaste can be saved. Under the right conditions, biogenic waste could become a strategic resource for achieving negative emissions, without the impacts on food security/land availability that other BECCS pathways might have.
- A Swiss case study showed that in order to achieve net negative H2 supply chains, BECCS processes with H2 production will be required.
- Costs for gasification based BECCS in Brazilian sugar mills were reported as 58 – 77 €/tCO_2.
- Costs for the production of carbon negative fuels in biorefineries with CCS were found to be 22 – 66 \$/tCO_2. Gasification based systems are able to capture up to 10 times more CO_2 from the same amount of input biomass than ethanol fermentation plants, while costs are comparable.

DAC

- Costs for methane produced from air captured CO_2, using amino-acid salts and renewable H2, were found to be 556 \$/tCO_2, which could be lowered to 365 \$/tCO_2 through process optimisation. Further cost savings are expected though scale-up.
- Novel amine functionalised solid sorbents with higher CO_2 capacity and lower volatility were presented. In addition, clarification on the H2O-CO_2 interactions was provided, supporting both carbamic acid formation and multilayer adsorption mechanisms. Process modelling highlighted the significant effect of temperature and humidity on overall process performance, thus local weather conditions will need to be considered during the design of DAC reactors.
- Costs for an ambient weathering process using MgO2 for CO_2 removal from air (in which MgCO3 is regenerated by calcination and then spread surrounding the plant to allow for repeated CO_2 capture) were reported as 43 – 159 \$/tCO_2.
- Negative emissions can be achieved via CO_2 mineralisation of MgO sourced from desalination of brine. This process results in the production of several sellable co-products, meaning the whole process could operate with a profit (4.5 \$/m3brine). If applied to all desalination brine, negative emissions of 231 $MtCO_2$/a could be achieved. This potential will be limited by market saturation of the co-products but will also be expanded by a growth in desalination plants.

CO_2 Utilisation

- One of the features of the CO_2 utilisation sessions presented during GHGT-15 was the concept of single-stage capture and utilisations. The production of dimethyl ether (DME), and its use as an energy carrier, was one of two examples during the conference. The rationale for this line of research is the use of DME as a high density energy and hydrogen carrier. DME can provide a climate neutral; chemical feedstock and fuel and contribute to emissions reduction whilst offering security of supply.

- OME (oxymethylene) synthesis was another route explored in this research as it can be used for road fuel when blended but is more expensive compared to DME. DME based fuel still remains uncompetitive with fossil fuels but are effectively liquefied renewable power sources especially for long-haul transportation with a low CO_2 footprint.

- In another single stage process an experimental integrated carbon capture and utilisation could be used to convert CO_2 to formic acid and formaldehyde. The concept is based on a classic ammonia post-combustion CO_2 capture system which produces formic acid that has the potential for further conversion to formaldehyde.

- GHGT-15 included two sessions dedicated to CO_2-EOR. Although this is a mature technology it is reassuring to see strong advances in monitoring techniques especially where they can be used to track the presence of injected CO_2. The technology is largely used in the US, however, the Bangdung Institute in Indonesia is conducting initiatives to stimulate its potential deployment in the country. A source-sink database for CO_2-EOR has been established to screen suitable natural sources of CO_2, and their proximity to depleted oil field reservoirs. The three most promising candidate oil fields have an estimated storage rate of 9,650 tonnes per day.

Environmental impacts & remediation

- Policy approaches and long-term monitoring are both important in assuring storage permanence, but are not the key assurances. Most of the permanence is in the site selection and operation and petrophysics has high value power in trapping CO_2. The three key components of permanence are geotechnical aspects, policy and legal, and public opinion and information seeking. Permanence means different things to different people, and in different contexts.

- There has been new work in testing advanced sealants to address the potential of CO_2 seepage behind well casings and a review of the implications for carbon management. It is recognised that shales are complicated and have lots of complexities that need to be considered in any project. Hydraulic testing of the test sealants used revealed good sealing of the entire borehole, but questions remain. The exact flow path geometry and characteristics, penetration depth of sealants, interaction of sealants with cement, casing and host formation, and degradation of the sealants, cement and casing require investigation. Overcoring of the well system will be done in future work to assess damage extent and the performance of the sealants.

- Work has been done on an effective indicator for CO_2 concentration in seawater (using data from the Tomakomai project, Japan and investigating locations where volcanic leaks of CO_2 occur naturally). This work shows that the possibility of misidentification from natural fluctuations, or false positives, can be reduced. This approach combines the methods of four indicators and is effective in detecting CO_2 leakage at mass emission points.

It must be noted that depending on the detectable distance and other factors such as ocean current velocity, there is a possibility that false negative signals may occur. More work is needed to see the relationships between these factors.

- Technology Centre Mongstad (TCM) aimed to provide an overview of exposure over time for the Centre and to provide future CO_2 capture plans with an indication of the expected background concentrations around an amine plant. The main findings show that background levels are in compliance with today's OELV (Occupational Exposure Limit Value) and the detection of N-PZ (nitroso-piperazine) in proximity to the plants probably indicate that the background levels originate from the amine plant. Laboratory experiments show that Thermosorb-N filters can give reliable results and work environment assessments.

Transport & Shipping

- Hub and transportation of CO_2were significant new topics at GHGT.
- Research into optimum pressure conditions for transportation have been investigated at both 7 and 15 bar. The 7 bar solution has a higher cost for liquefaction, but lower intermediate storage cost and cost for ship tanks. Optimisation modelling suggests higher 15 bar scenarios are less favourable from a cost perspective. Two other studies on engineering solutions and cost optimisation have endorsed a preference for a 7 bar transportation pressure.
- The establishment of a hub might reduce the cost of a CO_2 network due to the volumes transported via ships or pipelines, but it will require co-operation between different companies especially on the levels of impurities due to mixing of CO_2 from several different sources.
- Hubs can offer benefits by acting as a buffer so that continuous supply can be delivered to large storage reservoirs without intermittent disruption or the associated compromised injectivity.
- Scalable algorithms have been developed for designing large-scale CO_2 capture and storage infrastructure.
- Network analysis has now been applied to the storage capacity of depleted gas fields in the Dutch sector of the North Sea. Different injection conditions (pressure and temperature), injection rates and platform / well configurations have been modelled to determine optimal storage rates. The transport and injection system can be tailored to CO_2 supply characteristics. Intermittent supply requires flexibility that includes wells with low minimum rates. The envisaged systems need to be engineered to minimise shutting in of wells.
- An ALIGN-CCS study to develop transport and storage scenarios from 2020 to 2070 has focused on the Porthos consortium based on Rotterdam and the Athos consortium based on the Amsterdam – Ijmuiden area. Depleted gas fields in the Dutch sector of the North Sea can provide ample storage capable of accomoodating 10 Mt CO_2 per year by 2030 and for a subsequent period of 40 years. An average unit cost estimate for compression, transport and storage is €9 per tonne of CO_2.
- A shipping and transportation model based on southern Norway has been developed to obtain a minimum cost of a CCS chain. Pressure design for marine tankers plays a significant role in the cost of the chain with trade-offs between low conditioning costs and higher transportation costs. Individual pipelines from the Kollsnes shore-based distribution site to each storage field were more economical than a single pipeline with multiple connection points to individual fields. Economies of scale are achieved as the quantities of delivered CO_2 are increased.

Panelists at the Panel Discussion on New Business Models, from Day 1 of GHGT-15.

Panel Discussion 1: New business models

This panel discussion looked at the impact and effectiveness of new business models to stimulate investment in CCUS and discussed the role that governments can play in the development of these business models.

Current business models such as the US's 45Q or the California Low Carbon Fuel Standard, play an important role in stimulating new business models and will drive people to look at how incentives can be used and are crucial in enabling CCS to scale up and move forward. Confidence is needed in the risk profile of CCS projects and acceptability is still an issue, particularly with onshore storage in Europe. As more CCS projects are undertaken, more lessons will be learnt, more knowledge shared and business models will become clearer over time. Each and every business model will have different characteristics; every sector is different and will therefore need different models to help facilitate deployment.

Business models in CCS are technology-specific and not one will fit all situations; they should be built around technologies and different models will work differently for different sectors. Factors such as regional specificities are also important to consider in the development of CCS business models. Governments will need to consider taking on project risk, or facilitating integration of countries and projects to help facilitate wide scale technology deployment, rather than creating business models.

Panel Discussion 2: Improving Quality of Cost Estimation Techniques

Ed Rubin, Carnegie Mellon University, a distinguished professor whose research focuses on technical, economic and policy issues related to energy and the environment chaired this panel discussion. Together with IEAGHG's John Davison (now retired) and MIT's Howard Herzog, he is a founding member of IEAGHG's CCS Cost Network. Professor Rubin is a co-author of the oft-cited IEAGHG 2013 White Paper, "Toward a Common Method of Cost Estimation for CO_2 Capture at Fossil Fuel Power Plants". He pointed to three areas of current interest, aspects of which the five panellists would provide notable insights:

- Cost estimates for advanced, early-stage (pre-commercial, TRL: 3-7) capture technologies
- Cost estimates for capture in the industry sector
- Characterising uncertainty in the cost of capture

Simon Roussanaly, SINTEF Energy Research, opened with some thoughts on techno-economic assessments (TEAs) on industrial capture. While many such TEAs had been made, big discrepancies in cost estimates were common between studies. In large part, these discrepancies resulted from a lack of consistency between cases considered and differences in the cost methodology applied. He described, with examples, the impact some of these factors could make, as well as illustrating some of the challenges encountered in retrofit applications. He ended by pointing out that cost estimates for transport and storage required more serious attention than they were very often given.

Tim Fout, US DOE's NETL, followed by considering means to improve cost guidelines for advanced low-carbon technologies. As designs of advanced technology evolve and change with increasing maturity, Nth-of-a-kind (NOAK) plants costs for advanced technologies can be misleading. He stressed that the objective of the NOAK estimate must be clear, i.e. whether it is to estimate aspirational costs or to derive expected costs, with the choice of costing methodology dependent on the objective selected. He described the many different factors that must be considered when estimating first-of-a-kind (FOAK) costs. He went on to describe the hybrid approach for estimating NOAK costs– obtained by estimating FOAK costs and applying learning curves – which, in his opinion, provides assessments that are more realistic.

Next, **Mijndert van der Spek**, Heriot-Watt University, shared his thoughts on improved guidelines for uncertainty in techno-economic assessments. He advised that uncertainty should not be minimised or masked, and should not be confused with accuracy. He stressed that a large uncertainty in estimated costs was quite acceptable for less mature technologies, in fact, quite normal. Importantly, uncertainty analysis, for which several new approaches have been developed recently, can be extremely helpful in identifying, for example, the parameters the technology is most sensitive to and the areas where improvement might be made. **Li Chen**, Total Gas, Renewable & Power, described Total's work on the activities and challenges of techno-economic assessment in CCUS R&D. For technologies at TRL 2-6, she discussed why TEAs were undertaken (investment decisions and R&D prioritisation) and what parties performed them (with different attributes, cost estimators and process development engineers). TEAs undertaken by Total include single capture technologies and different modes of CO_2 transport, through full chain industrial CCS to blue and green hydrogen – estimating in each case FOAK and NOAK costs. In presenting this work, she described the many challenges to be overcome, from the methodologies employed to the need for transparency in selecting data and presenting results.

Andrea Ramirez, Delft University of Technology, is Editor-in-Chief of the International Journal of Greenhouse Gas Control (IJGGC), in which many of the TEA studies relating to CCUS are published. She discussed the IJGGC's position relating to guidelines and in answering the basic questions relating to (new) technologies, which are essentially: "Does it work?" and "At what cost?" TEAs provide an assessment of 'likely' costs, together with an indication of accuracy. To this end, their credibility depends on the reliability of the process creating them that, in turn, relies on the methodology used, the data drawn on and the assumptions made. By far the majority of papers on the topic submitted to the IJGGC address capture, with a very small number addressing full-chain CCS. Authors are expected to use best practice approaches, with results reproducible by third parties – transparency and consistency are key.

An excellent question and answer session followed, with a range of important issues raised by attendees and commented on by panel members. Placing some perspective on the cost of CCS was interesting, such as the 1% increase in the production cost of a new house from using zero carbon cement, with similar narratives for the use of low-carbon steel on the cost of vehicle manufacture. Finally, and importantly, it was pointed out that a White Paper containing much of the information shared by panellists would shortly be publicly available in open access on Zenodo.org. Various parts would also be or will already have been published in the IJGGC.

Panel Discussion 3: Decarbonising Natural Gas

The back drop to the decarbonisation of natural gas is the underlying reality that it remains a very significant global source of energy. The CO_2 content can also be significant and requires separation and removal. The panel, chaired by **Lincoln Patterson** from the Australian National University also included **Mark Trupp**, Chevron Australia and **Philip Ringrose**, from the Equinor Research Centre. Mark outlined the progress and challenges presented by the relatively recent Gorgon project; and Philip gave a perspective of Equinor's experience gained from the Sleipner and Snøhvit projects.

Philip opened the discussion by giving a succinct summary of the route to a net-zero future. The magnitude of the extent of decarbonisation depends on the starting point for different countries. Sweden is an excellent example of a country with an advanced industrial economy which has already achieved a low natural emission rate of ~10g/kWh, but this is exceptional. Many countries are still heavily dependent on fossil fuel sources and have economies with industrial sectors that are hard to decarbonise. Philip stressed that 'total system emissions' must be considered and not just individual components. Although renewables can achieve low carbon fuel sources they still require integration with other energy sources. Here, CCS offers low carbon sources for hydrogen which can be used for transport and industry which will be necessary to achieve net-zero targets by 2050.

Lincoln then set out the importance of the contribution from the natural gas industry. The sector's core skills in development and technological expertise can deliver CCS and the expansion of a hydrogen economy. The Gorgon experience was then highlighted by Mark. He emphasised the project consortia's skills in subsurface interpretation. Multi-disciplinary teams of geologists, geophysicists and production technologists are required to prioritise tasks, conduct uncertainty assessments and risk evaluations. It would be hard for other industries to develop CCS rapidly without these core skills. Philip added that the pace of CCS development needs to accelerate and gain from existing projects. Information exchange from conferences like the GHGT series has an important role in this regard.

The concentration of CO_2 in natural gas varies widely. In the Norwegian sector, exemplified by Sleipner and Snøhvit, CO_2 concentrations are 5- 10% whereas Gorgon has ~14% although gas from different sources is blended to reduce the CO_2 concentration. The Gorgon consortia are exploring ways to reduce operation costs by retaining natural reservoir pressures as a means of reducing the energy demand required to repressurised injected CO_2. The investment and operational costs also depend on reservoir quality and the infrastructure requirements. Sleipner, for example, has a multi-darcy quality reservoir but still required an additional small platform. Snøhvit had the advantage of an onshore gas separation and recompression plant. Offshore facilities may be necessary elsewhere. Lower permeability reservoirs will require more wells for mega-tonne scale sites.

The was a consensus amongst the panellists that as global energy demand is unlikely to decrease CCS should be part of the energy mix if a decarbonised economy is to be achieved in a limited timescale. Blue hydrogen (sourced from fossil fuels and linked to CCS) currently costs ~2/kg, whereas Green hydrogen (produced from electrolysis from renewable sources of energy) costs ~$4/kg. Consequently Blue hydrogen is the best economic option now although with economies of scale the cost of Green hydrogen should fall. Access to renewable energy, and especially the related spatial requirements to meet electrolysis demands at a significant scale, might constrain the production of Green hydrogen. The transition to a hydrogen economy is now hotly debated and there is a lack of realism on how it can be achieved within a limited timescale. The introduction of incentives is being contemplated in the United States. Philip raised a connected conundrum. If, for example, Norway exports natural gas to Germany then should the CO_2 be shipped back to Norway or should hydrogen be sent and the CO_2 retained in Norway.

Feedback from the audience questioned what infrastructure requirements would be necessary. A new hydrogen pipeline network could be developed or blue hydrogen could be produced at customer locations thereby avoiding a separate hydrogen pipeline. Other solutions include the addition of hydrogen to natural gas pipelines and the use of old natural gas pipelines for CO_2 transport. The lower viscosity of hydrogen will have implications for pipeline specifications. Embrittlement is another potential issue and is the subject of current research.

Other future options were mentioned including the use of ammonia in the transport sector. Early demonstration projects will be necessary for any innovative concept to build confidence and demonstrate success before attracting the investment for large-scale projects. Equinor is already involved in an ammonia pilot shipping project.

Low gas extraction from reservoirs shows that gas is naturally retained. Understanding trapping mechanisms is a perpetual area of investigation and future storage sites need to be selected based on their reservoir properties.

Lincoln change the direction of the discussion by asking the other two panellists what skill set is required especially for students thinking of a career in CCS. Mark responded by highlighting that in his experience from Shell, and now Chevron, expertise used for oil and gas exploration and production is transferred to CO_2 subsurface storage. New career entrants need to adopt a flexible approach to career development and be prepared to transfer acquired skills to new areas.

Lincoln concluded the session by posing the question - what would you have done differently? Both the panellists commented that learning from experience helps enormously especially in risk and cost reduction. Overall maturity is a key consideration, for example, the approach to injectivity and the enhancement of monitoring systems. Regulators also need to understand what is required to regulate CCS projects to ensure that low risk CCS projects can be implemented. Part of the problem with CCS is a negative association with the oil and gas industry rather than trying to understand the magnitude of the challenge and an appreciation of the mix of technological solutions required to meet net zero targets. There is also a perception that the success of Sleipner was a fluke. Experience shows that this was far from the case. There were initial injectivity problems and considerable research has been necessary to understand the reservoir and CO_2 behaviour within it. Sophisticated monitoring techniques are also necessary to track CO_2.

What is becoming clear is that the pioneers in CCS, including Shell, Total and Equinor have made very significant progress and are now in dialogue with industrial customers across Europe who are seeking permanent CO_2 storage.

Ganesh Dasari of Exxon Mobil gave an update on CCUS in the oil and gas industry at GHGT-15

Panel Discussion 4: CCUS in the Oil and Gas Sector

The challenges faced by the oil and gas sector, and the associated development of CCUS, were illuminated in the fourth panel discussion of the GHGT-15 virtual conference. A North American perspective was presented by **Ganesh Dasari** from ExxonMobil, **Scott Wehner** of CaprockCarbon, **Tim Wiwchar** of Shell Quest and **Nigel Jenvey** from GafffneyCline. **Tidjani Niass** of Aramco and **Aaesha Al Keebali** from ADNOC contributed a view from the GCC countries.

All the presenters highlighted the maturity of the oil and gas sector and how its collective expertise is helping to develop CCUS. Scott Wehner emphasised that although CO_2 Enhanced Oil Recovery (CO_2-EOR) is now a well-established practice it does depend on sound reservoir engineering, the injection pattern and flood control. It currently depends on CO_2 from low-cost sources as well as technical expertise. The 45Q tax credit does work but would be more effective if it was higher and better if it could be traded. The challenge for CO_2-EOR in the GCC region is the lack of incentive to implement it given the low oil production costs. However, CO_2-EOR is being implemented in both Abu Dhabi and Saudi Arabia. Both these countries have strong aspirations to reduce carbon emissions especially as part of a circular carbon economy where CCUS is integrated with other key activities including desalination.

The success of Shell's Quest project has demonstrated that cost reduction as well as technical achievement can be achieved. As a pioneer project Shell have been able to identify significant cost savings for future projects by, for example, modular construction. The company believe collaborative ventures and the prospect of industrial hubs will further advance CCUS. Supportive policies at national and international levels will also be necessary.

A comparison with the development of renewable energy technologies was discussed. Wind and solar energy have benefited from policies specifically designed to incentivise cost reduction which was led to dramatic falls in electricity prices. In contrast CCUS faces a low unit price for carbon which makes investment unattractive unless the carbon price is raised to a more realistic level.

Perhaps the biggest challenge for any CCUS development, particularly the storage component, is that each project is governed by site-specific conditions which need to be determined for each case. Nevertheless there is growing optimism across the oil and gas sector as larger integrated CCUS projects are being planned and implemented. Live projects will help to build confidence and efficiency leading to cost savings.

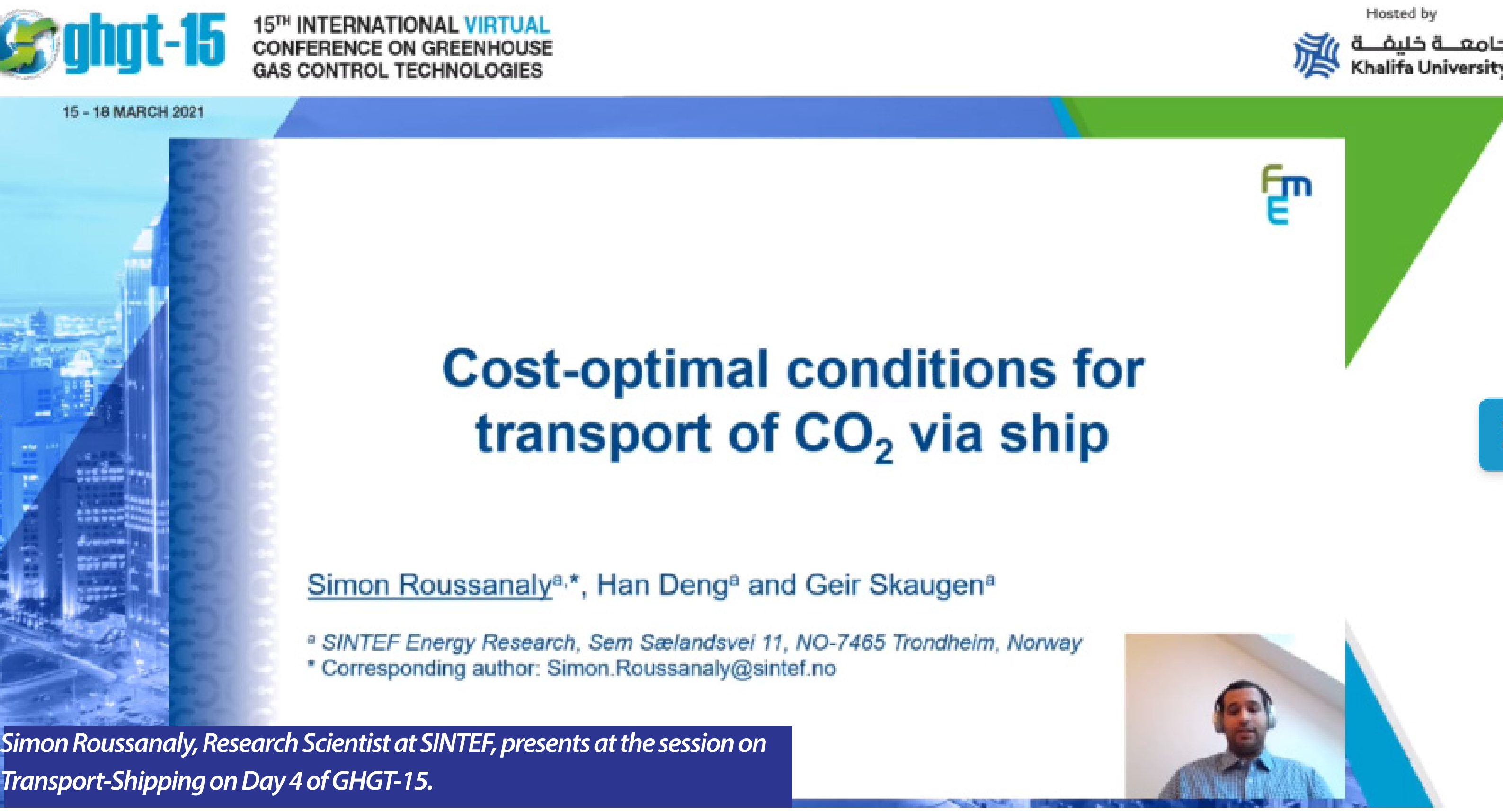
Panel Discussion 5: Closure issues, - CA LCFS 100 years and EPA 50 years vs EU performance based

The fifth panel discussion at GHGT-15 focussed on closure issues with CO_2 storage projects, particularly looking at US regulations compared to policies in the EU. **James Craig** (IEAGHG) chaired this panel and welcomed six international panellists: **Susan Hovorka** (GCCC, The University of Texas at Austin), **Marcella Dean** (Shell Global Solutions International B.V), **Matthias Raab** (CO_2CRC), **Ziqiu Xue** (Research Institute of Innovative Technology for the Earth (RITE)), **Neeraj Gupta** (Energy Division, Battelle) and **David Riestenberg** (Advanced Resources International, Inc.). The expert panel gave perceptive insights into various applicable projects and discussed whether current policies and regulations are appropriate for determining site closure, how to verify stabilised CO_2 plumes and the considerations for scale-up.

It seems clear that the US approach to site closure is rather cautious and prescriptive, whereas the EU approach is more performance and risk assessment based. There was some concern that the US procedure is not targeted towards its intended purpose, and is vague so not required to be risk-based which is a potential weakness. A performance-based approach is better able to deal with any problems within the project timescale so that success can be achieved. In the EU, a well-designed post-closure plan facilitates a timely handover when it is based upon a monitoring and performance-based plan rather than a purely time-based approach. When an operator sees changes in the risk profile of a project evident from data acquisition with the MMV (monitoring, measurement & verification), early corrective measures can be undertaken. Regulators can be reassured and develop trust with the operator. Moreover, a detailed risk assessment plan, for example based on a bow-tie evaluation, can be adapted throughout the life of a project from inception to closure.

The concept of scale-up is interesting as some of the projects have been small-scale pilots. The approaches to post-closure have been shown to be appropriate but this experience needs to be adapted to what is likely to be necessary at a larger size. Performance-based indicators will be important in scale-up and the definition is and will be project-specific; a pragmatic approach is required. The middle ground is to be clear on what is to be achieved and how to do it; key performance indicators (KPIs) can change and be adapted over time but it is important to have an understanding of the risk profile throughout.

Every project irrespective of scale will have unique challenges and it is important to define what is expected of a project. Anomalies which are not immediately evident should be expected and operators should be able to explain their origin. The fundamental knowledge to implement projects is already there, and now the confidence in subsurface models, and monitoring techniques, should be taken forward. As experience continues to grow, the storage and monitoring communities are gaining in experience and confidence and they should not shy away from moving towards large scale CO_2 storage.



Simon Roussanaly, Research Scientist at SINTEF, presents at the session on Transport-Shipping on Day 4 of GHGT-15.

Panel Discussion 6: Post-Combustion Capture Technology: Progress, Gaps and Future Direction

A formidable panel, Chaired by EPRI's **Abhoyjit Bhown**, was brought together to discuss the status of PCC technologies. While most capture technologies at TRL8 or TRL9 are amines, there are several promising second and third generation technologies under development and attracting strong interest. For the purposes of this discussion, each of the panelists described the status of a particular capture technology.

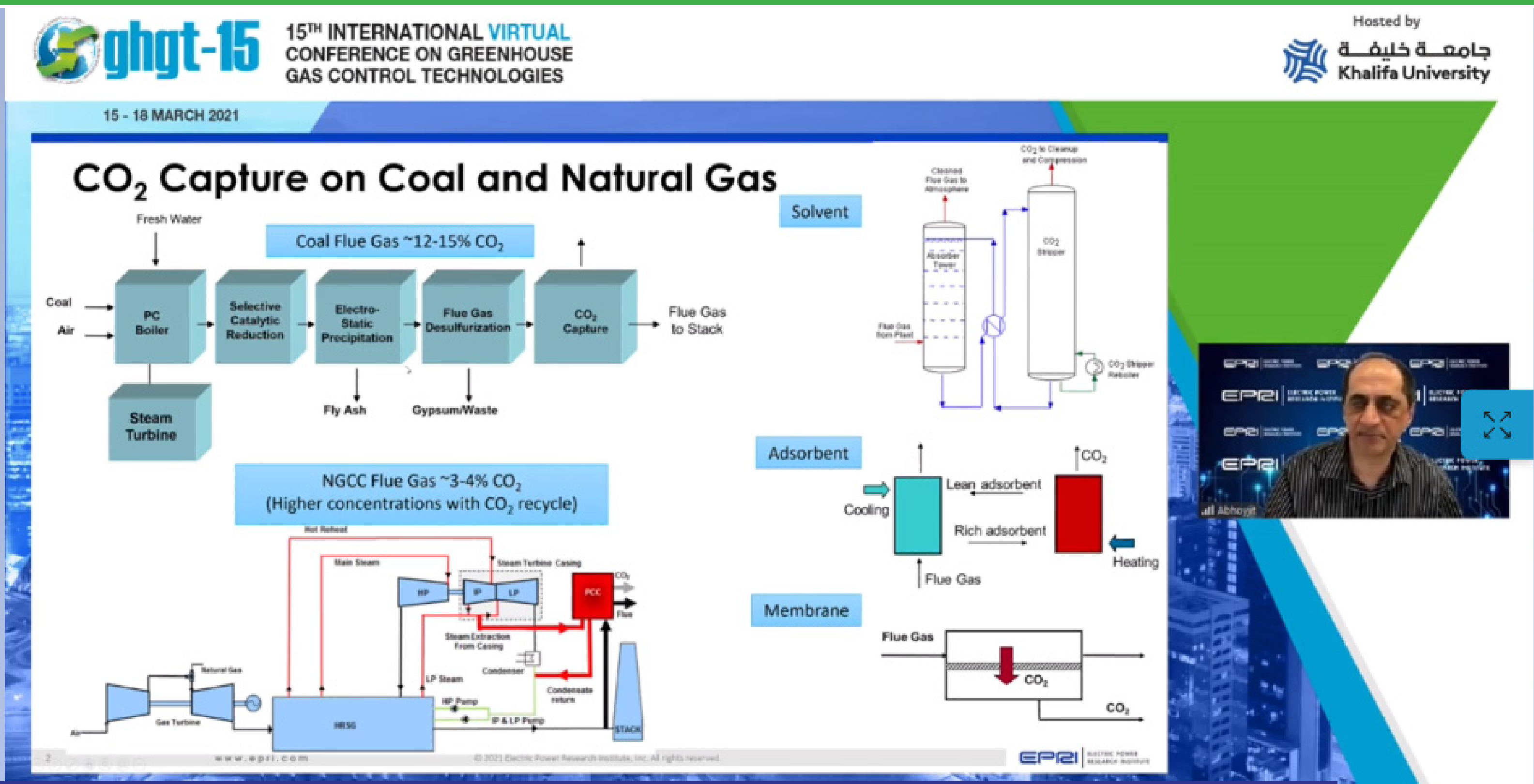
First up was **Gary Rochelle,** University of Texas, who described very succinctly the advanced status of amines for this particular task. Several second generation amines were well established and had been demonstrated at scale, of which well-known examples include KS-1, DC-103, PZAS and Cesar-1. These solvents worked very well. Power requirements were low, approaching the theoretical minimum of 110 kWh/t – with the best now around 210 kWh/t. Amine emissions are no longer the problem they once were, though some effort was still needed on amine oxidation. Challenges remaining included the capital cost, which needs to come down, and the realisation that 99+% efficiency was now the target. All in all, second generation amines were presently hard to beat.

Yongqi Lu, Illinois State University addressed the status of biphasic solvents. He described the different types of these solvents, which were 'CO_2 loading triggered' and 'thermomorphic', with current work at the university developing a new class of ionic strength switchable solvents. There were potentially a list of advantages of using biphasic solvents, the development status was still at the lower TRLs, with testing at small scale and a lot of development effort lying ahead.

Marti Lail, RTI International, presented the status of water-lean and non-aqueous solvents (NAS). With a focus on reducing CAPEX and limiting OPEX, he felt their developmental status lay somewhere between amines and biphasic solvents. Parametric and long-term testing had been undertaken at SINTEF on a 20 t/d rig, with testing presently ongoing at TCM, where the focus was on solvent performance, degradation, techno-economic and environmental assessments. Testing at TCM was planned for completion towards the end of 2022.

Tim Merkel, Membrane Technology and Research (MTR), discussed the status of membranes. Membranes had several inherent advantages, including the fact that, unlike amines, there was no chemical handling or disposal issues, and membranes required relatively little water usage. Wh
ile today in the TRL6 to TRL7 range, effort was underway to move them towards TRL8. Membranes were well suited to capture rates of 50% to 70%, while costs rose quickly at higher rates – so, not really suitable for targeting 99%. MTR's Polaris membranes had been tested at NCCC or > 11,000 hours. A 20 t/d test campaign at TCM was planned to begin shortly (Spring 2021) and a FEED (front end engineering design) study for 150 t/d at Wyoming's Dry Fork Station had recently been completed. In conclusion, Tim felt the performance and durability of membranes were promising, with the potential for cost and performance improvements as the technology was scaled up.

Takeshi Okumura, Kawasaki Heavy Industries (KHI), covered the status of solid sorbent technology. KHI was developing its own technology – named Kawasaki CO_2 Capture (KCC) – an amine-impregnated porous material. The amine and degree of impregnation was customised to the particular application, depending predominantly on the concentration of CO_2 in the gas to be treated.



Abhoyjit Bhown, EPRI, chaired Panel Session 6: Post-Combustion Capture Technology: Progress, Gaps and Future Direction

The CO_2 was recovered at ~60°C using waste heat, so low energy. Testing had been completed on a 10 t/d fixed bed, with further development using a 5 t/d moving bed design. Improvements had been made, for example, virtually eliminating pulverisation of the sorbent during operation. With support from several other Japanese organisations, pilot scale testing was now planned at a coal-fired power station. Successful small-scale testing of the sorbent had also been undertaken at Wyoming's Integrated Test Centre (ITC) at Dry Fork Station.

Adam Berger, EPRI, described the merits and challenges associated with cryogenic CO_2 capture. Separating as a solid on chilling the flue gas, dense phase CO_2 is captured without the need for chemical separation. Potentially, a relatively low-cost process, it can achieve high capture rates, typically 95% to 99% though, to go higher than this becomes quite energy intensive. In addition, dense phase compression requires only a small fraction of the energy required for a gas, the energy penalty is purely electrical, and performance not limited by diffusion into a separation medium. A low-cost, low-energy process, the equipment required for cryogenic separation is generally well advanced. Challenges of capture using cryogenic separation include those associated with heat exchange and thermal management, the potential for plugging during recovery of the solid CO_2, and ice formation due to moisture in the flue gas. Sustainable Energy Solution's Cryogenic Carbon Capture (CCC) process has been tested at the 1 t/d scale. There is also Carbon America's FrostCC process, which is presently undergoing testing at laboratory scale.

Many interesting points were raised in the subsequent discussion. The broad thrust seemed to be that amines were clearly the technology to beat. The current state of the climate required that capturing CO_2 needed to be deployed at scale sooner rather than later, with a focus on the leading technology option, support for its deployment (in whatever form that takes – 45Q, California's LCFS, …), and R&D continuing in parallel on other technology options. Emphasising this approach, it was pointed out that, with the 'hub' approach to CCUS garnering significant attention, 'downsizing' of applications to address smaller-scale plants may, in future, bring some of the other technologies more into play.

What was new?

- **Salt water analogue for CO_2 storage, US Gulf Coast**: Data shows that in the US Gulf Coast region alone, 1,500 currently active water disposal wells can inject the volume equivalent of more than 1 Gt CO_2/yr with an average injection rate of 20,000 bbl/day (0.8 MtCO_2/yr) per well.
- **Porthos.** An ALIGN-CCS study to develop transport and storage scenarios from 2020 to 2070 has focused on the Porthos consortium based on Rotterdam and the Athos consortium based on the Amsterdam – Ijmuiden area. Depleted gas fields in the Dutch sector of the North Sea can provide ample storage capable of accommodating 10 Mt CO_2 per year by 2030 and for a subsequent period of 40 years.
- Development of a **hydrogen supply chain from Australia to Japan**. It includes a pilot scale tanker and loading facility in the Port of Kobe, Japan. A trial has also begun to test the viability of shipping ammonia from Saudi Arabia to Japan.
- The production of **dimethyl ether (DME)**, and its use as an energy carrier, was one of two examples during the conference which is of growing interest. OME (oxymethylene) synthesis was another route explored in this research as it can be used for road fuel when blended but is more expensive compared to DME.
- **Costs for methane produced from air captured CO_2**, using amino-acid salts and renewable H2, were found to be 556 \$/tCO_2, which could be lowered to 365 \$/tCO_2 through process optimisation. Further cost savings are expected though scale-up.
- For **BECCS** cost optimal deployment of BECCS in different regions has been identified. The role of BECCS in the optimal design of net negative hydrogen supply chains has also been established plus cost and negative emissions potential for biorefineries with CCS concepts.
- New **DAC** developments include: integration of DAC with energy storage systems; and novel amine functionalised solid sorbents plus a better understanding of the moisture co-adsorption mechanism on those sorbents.

Greenman Award


Mike Monea is awarded the Greenman Award at GHGT-15

The Greenman Award, for making an outstanding contribution to CCS, was presented to **Mike Monea**, former President and CEO of the International CCS Knowledge Centre which he helped to establish with BHP Billiton and SaskPower. Leading this centre was a reflection on Mike's hard work as the president of Carbon capture and storage initiatives at SaskPower where he was in charge of creating and building the world's first carbon capture plant for a coal power unit valued at \$1.5 billion CDN, the Boundary Dam CCS project.

Considered to be the Nobel prize of the CCS world, only 13 people have received the Greenman Award since its inception in 1996, including this year's winner. An ancient symbol found in many cultures throughout the world, the Greenman represents the union of humans and the natural world.

Concluding remarks

In their concluding remarks and acknowledgements, **Tim Dixon** and **Prof. Kelly Thambimuthu** of IEAGHG highlighted that the conference had covered the whole spectrum for CCUS, not just the range of technologies but also the spectrum from initial scientific ideas to experiences from large-scale projects and on to addressing commercial deployment and financing. The conference, whilst virtual, had still acted as the main global gathering of CCUS interests.

Prof. Mohammad Abu Zahra, conference Technical Co-Chair and Professor of Chemical Engineering at Khalifa University, gave the concluding remarks on behalf of the GHGT-15 host. In his remarks, he highlighted the importance of CCUS to the region and the influence of hosting GHGT-15 on the deployment of CCUS technologies in the Gulf region. He acknowledged the stakeholders who supported the conference and shed a light on the Khalifa University experience in hosting such an international event.

The next GHGT

GHGT-16 will be held in the French city of Lyon which has one of the largest Renaissance quarters in Europe and a 2,000 year old UNESCO world heritage site. As the French gastronomic capital Lyon offers a wide choice of restaurants and "bouchons", a regional Lyonnaise cuisine. The conference centre is situated between the Rhône and the "Parc de la Tête d'Or" in an area of 105 hectares including a 16 hectare lake. The centre is near the "Cité Internationale" designed and built by the highly innovative architect Renzo Piano and the late landscape artist Michel Corajoud. The district forms a dynamic events complex, including centres of congress, casinos, cinemas, hotels, restaurants and bars.

The Lyon Convention Centre has been designed to be environmentally harmonious. It boasts 24,000 m^2 of flexible meeting spaces including three amphitheaters (300, 900 and 3,000 seats) and 35 fully equipped meeting rooms.

GHGT-16 is hosted by ClubCO$_2$, the leading French CCUS team, supported by four major and well-recognised institutions: ADEME, BRGM, IFPEN and Total.

GHGT-15 Sponsors

IEAGHG offers a major vote of thanks to the conference sponsors. Their support was instrumental in making this conference happen. In addition, recognition goes to Khalifa University, the conference host organisation, and MCI, the conference organiser, both for the support given to the organisation of the conference and for their assistance in the organisation of the virtual conference.

Southern Company | NATIONAL CARBON CAPTURE CENTER

CO_2 Capture Project
A PIONEERING LEGACY

equinor

GASSNOVA

OGCI
OIL AND GAS CLIMATE INITIATIVE

TotalEnergies

Host Organisation

جامعـــة خليفـــة
Khalifa University

Conference Organiser

mci

Evaluating technology options to mitigate greenhouse gas emissions

ieaghg

Hosted by

جامعة خليفة
Khalifa University

IEA Greenhouse Gas R&D Programme

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

Tel: +44 1242 802911
mail@ieaghg.org
www.ieaghg.org