Technology Collaboration Programme
by iea

Evaluating technology options to mitigate greenhouse gas emissions

7th Post Combustion Capture Conference Summary

Pittsburgh, Pennsylvania, USA

25th - 28th September 2023

IEA GREENHOUSE GAS R&D PROGRAMME

The Pittsburgh Skyline

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About IEAGHG

Blazing the way to net zero with leading CCS research. *We advance technology to accelerate project development & deployment.*

We are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate 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. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

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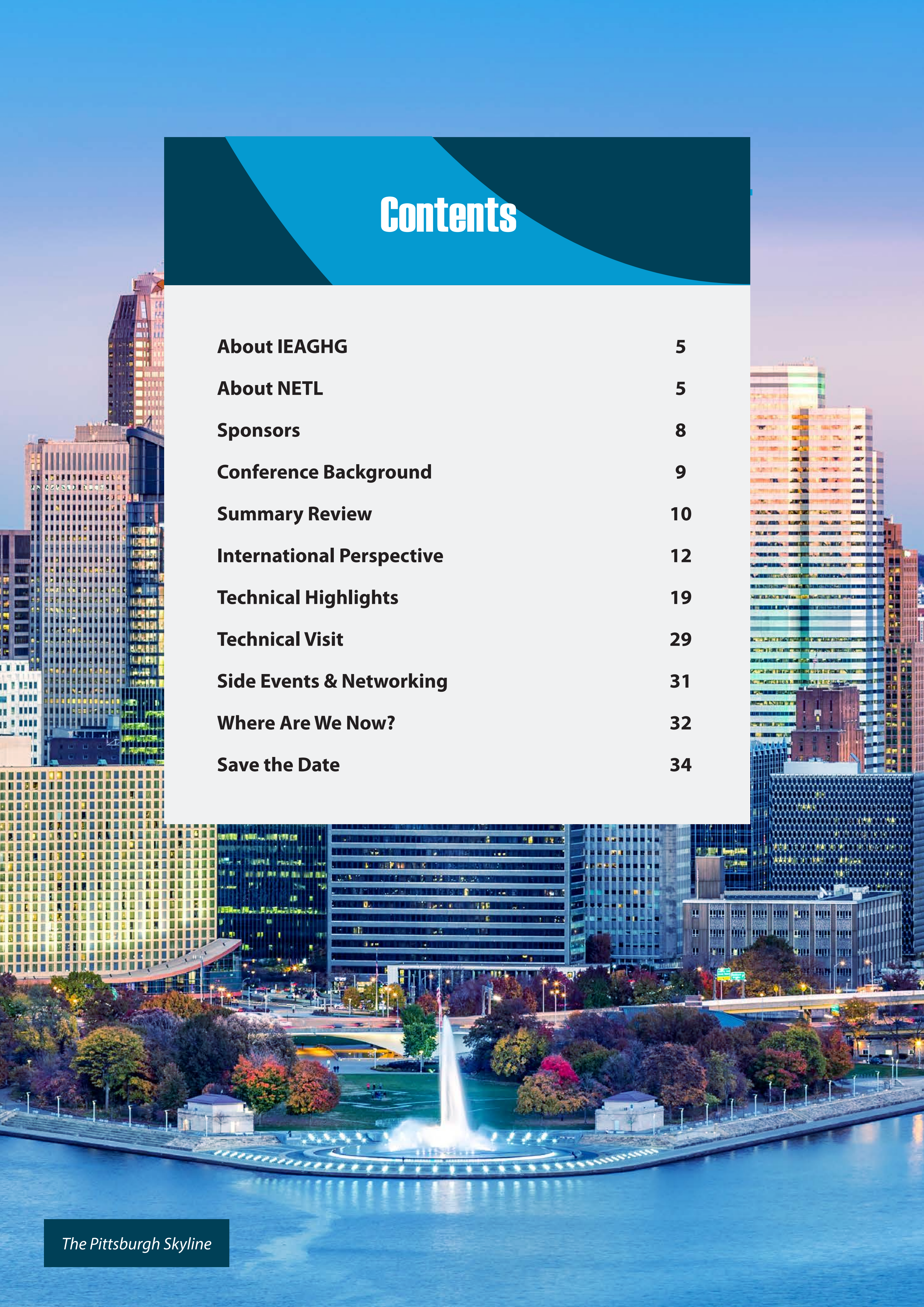

The Pittsburgh Skyline

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We believe that sharing knowledge is vital to achieving net zero. That's why we host the world's leading CCS conference, the Greenhouse Gas Control Technologies Conference (GHGT) and many other events throughout the year. These bring together top experts from across the field to advance the development and deployment of CCS technology.

As a not-for-profit technology collaboration programme (TCP) of the International Energy Agency, we are committed to:

- *Uphold the highest research standards.*
- *Fuel collaboration between the public and private sectors.*
- *Deliver integrated, cost-effective solutions that drive down carbon emissions.*

About NETL

NETL is a U.S. Department of Energy national laboratory that drives innovation and delivers technological solutions for an environmentally sustainable and prosperous energy future.

Through its world-class scientists, engineers and research facilities, NETL is ensuring affordable, abundant and reliable energy that drives a robust economy and national security, while developing technologies to manage carbon across the full life cycle, enabling environmental sustainability for all Americans, advancing environmental justice and revitalising the economies of disadvantaged communities.

Leveraging the power of workforce inclusivity and diversity, highly skilled innovators at NETL's research laboratories in Albany, Oregon; Morgantown, West Virginia; and Pittsburgh, Pennsylvania conduct a broad range of research activities that support DOE's mission to ensure America's security and prosperity by addressing its energy and environmental challenges through transformative science and technology solutions.

A flavour of PCCC-7

PCCC-7 In Numbers

188 *Delegates - the largest PCCC ever*	**80** *Technical Presentations*	**17** *Nations Represented*
3 *Plenary Sessions*	**9** *Keynote Speakers*	**10** *Conference Themes*
18 *Technical Sessions*	**1** *Poster Session*	**4+6** *Sponsors and Exhibitors*

Conference Themes

Amine Oxidation

Process Configurations

Demonstration Activities

Environmental Impacts

Process Applications

Process Modelling

Modelling Novel Concepts

Alternative Concepts

Amine Degradation

Novel Amines

Sponsors

Many thanks to our generous sponsors and co-hosts without whom this event would not have been possible.

PCCC-7 Steering Committee

Keith Burnard (Chair)
IEAGHG

Krista Hill
NETL

Paul Feron
CSIRO

Jon Gibbins
UKCCSRC

Kazuya Goto
RITE

Brent Jacobs
CCS Knowledge Centre

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University College London

Frank Morton
NCCC

Gary T Rochelle
University of Texas at Austin

Hallvard Fjøsne Svendsen
NTNU

Suzanne Killick
IEAGHG

Jennifer Diday
NETL

Conference Background

Following the success of twelve international CO_2 capture network meetings held worldwide since 2000, the decision was made to evolve this network into a full-fledged conference, now known as the Post-Combustion Capture Conference (PCCC). The IEAGHG PCCC conference series which was first organised in 2011 has established itself as the world's leading conference series discussing advancements and paving the way for innovative solutions in post-combustion capture technologies.

Each event in this conference series serves as a pivotal platform for showcasing advancements in Post-Combustion Capture. It spans the gamut from cutting-edge research to practical demonstrations. The series highlights a range of developments, from innovative solvents to ground-breaking separation methods. Additionally, it addresses various aspects including cost to environmental impacts.

Owing to its acclaimed reputation, the conference series has evolved into a hub for the presentation of high-impact papers and posters. This makes it an ideal destination for those seeking a comprehensive understanding of specific facets of current PCC research, as well as for those aiming to stay informed about the current global state of post-combustion capture.

The conference has gained such prestige that it attracts high-quality research presentations and attendees eager for detailed insights into the latest trends in post-combustion capture, or simply to stay updated on its global progress.

The inaugural PCCC conference was hosted in the United Arab Emirates in 2011. Since then, the conference has been organised in various countries, including Norway (2013), Canada (2015), the United States (2017), Japan (2019), held online (2021), and Pittsburgh (2023), reflecting its expanding scope and influence.

A unique aspect of these conferences is the opportunity they provide for delegates to participate in relevant technical visits, organised by the host organisation. In the past, these visits have allowed delegates to explore a variety of notable facilities. These include pilot test centres in Japan, Norway's Technology Centre Mongstad, and the U.S. National Carbon Capture Centre. Additionally, delegates have visited the world's first CCS demonstration on a power plant at Boundary Dam, as well as Aquistore's full-scale geological field laboratory for storage and in the latest and 7th edition of the series the US DOE/NETL research and demonstration facilities. Such visits offer invaluable practical insights into the real-world application of post-combustion capture technology.

The 7th edition of the Post Combustion Capture Conference (PCCC-7) was held on the 25-28 September 2023 and was jointly hosted by the IEAGHG, U.S. Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) and sponsored by Worley, Shell, and Mitsubishi Heavy Industries (MHI).

Summary Review

The 7th Post Combustion Capture Conference (PCCC-7) marked a significant and highly anticipated return to in-person gatherings, post-COVID. This signifies a shift from the virtual format of PCCC-6 to an engaging, face-to-face event was both refreshing and invigorating for all participants.

Globally recognised as the leading conference for exploring post-combustion capture, PCCC-7 lived up to its esteemed reputation. The conference provided an ideal platform to delve into the latest advancements and issues surrounding the development and application of this crucial technology. It was exciting to once again share experiences, ideas, and knowledge in an in-person setting, fostering an environment ripe for collaborative studies and networking.

The technical programme, featuring about eighty presentations across various parallel sessions, was the cornerstone of PCCC-7. These presentations, meticulously selected by the PCCC-7 Steering Committee from a plethora of submitted abstracts, spanned the full spectrum of post-combustion capture technologies. This ranged from ground-breaking research and demonstration projects to the exploration of alternative concepts and novel separation technologies, and discussions on cost and environmental impacts.

Jon Gibbins speaks at PCCC-7

PCCC-7 was underscored by the lively and interactive sessions where delegates actively participated in discussions and Q&A segments. The physical presence of attendees brought an added dimension of enthusiasm and connection that only in-person interactions can foster.

Over the course of the three-day PCCC-7 meetings, nine eminent keynote speakers graced the event with their insightful presentations and significantly contributing to the depth and breadth of the conference.

The conference kicked off with an impressive start on the first day, featuring welcoming addresses from two distinguished experts in the field of low-emissions technologies and CCS veterans. Professor Kelly Thambimuthu, Chair of IEAGHG and Dr David Miller, Deputy Director and Chief Research Officer at NETL, setting a tone of insight and collaboration. Mr. Jerad Bachar, President & CEO of VisitPittsburgh welcomed the delegates on behalf of the people of the Steel City, Pittsburgh.

The momentum continued into the second day with enlightening keynote speeches from Ms. Sarah Forbes, Deputy Director at the US DOE; Professor Edward Rubin of Carnegie Mellon University; and Ms. Patricia Scozzafave, Manager at Shell Catalysts and Technologies. Their presentations added depth and perspective to the discussions, enriching the conference experience.

The conference culminated on the final day with influential addresses from Dr. Dan Hancu, Division Director at the US DOE; Mr. Takashi Kamijo, Chief

Engineer at Mitsubishi Heavy Industries (MHI); and Mr. Rob Berra, Group Senior Vice President at Worley. Their presentations provided a comprehensive overview of the current state and future directions in the field.

Bringing the event to a fitting conclusion, Professor Gary Rochelle and Professor Jon Gibbins delivered the closing remarks, reinforcing the spirit of collaborative progress that defined the conference.

We extend our deepest gratitude to our generous sponsors and co-hosts who played a pivotal role in the success of PCCC-7. Special thanks to the US Department of Energy (DOE), the National Energy Technology Laboratory (NETL), Shell, Worley, and Mitsubishi Heavy Industries (MHI). Their support was instrumental in making PCCC-7 not only a reality but also a significant success. Their contributions ensured the conference maintained its not-for-profit ethos, allowing us to offer affordable registration fees while delivering an unparalleled experience.

Thanks to the host city, Pittsburgh also known as both 'the Steel City,' for its pivotal role in the U.S. steel industry, and 'the City of Bridges,' for its 446 bridges. Pittsburgh's historical significance thus added a remarkable backdrop to the event.

In conclusion, PCCC-7 transcended being merely a conference; it was a celebration of the resilience and collaborative spirit of the CCUS community, reuniting in person to advance a critical cause for our planet.

The IEAGHG cannot wait to bring forth the next instalment of the conference, PCCC-8, in France in 2025.

The Pittsburgh Skyline

International Perspective

As we reflect on the diverse and insightful contributions from PCCC-7, it becomes clear that the conference was more than just a platform for sharing cutting-edge research and advancements in post-combustion capture technology. It was a confluence of international expertise and experiences. By bringing together perspectives from around the globe, it provided a unique opportunity to exchange innovative ideas, discuss challenges, and explore collaborative engagements in the global pursuit of post-combustion capture solutions.

Kelly Thambimuthu
IEAGHG

Kelly Thambimuthu, the Chair of IEAGHG, who has more than 40 years of experience in the field of low-emissions technology, was a coordinating author of the UN Intergovernmental Panel on Climate Change (IPCC) special report on CO_2 capture and storage published in 2005. He is also a recipient of several awards, including as a contributing scientist to the Nobel Peace Prize awarded to the IPCC in 2007. Kelly highlighted that a 90% capture rate is insufficient to meet the global Net Zero Emissions (NZE) targets by 2050. He highlighted the pertinence of increasing the CO_2 capture rate to 99% to align more with the goal of a net-zero target. The increases in capture rates have been reported to result in a modest increase in the levelized cost of electricity (LCOE) and the costs associated with CO_2 avoidance for natural gas combined cycle (NGCC) and ultra-supercritical pulverized coal (USC PC) power plants..

Furthermore, Kelly underscored the vital role of carbon dioxide removal (CDR) technologies, as demonstrated by the UK's Drax Power Station's planned conversion from coal to BECCS (bioenergy with carbon capture and storage). He showcased Drax's transformation from the UK's largest coal power station to its ambition to become the world's first large-scale BECCS plant by 2027 and a net-negative company by 2030, serving as a paradigm for economically viable and sustainable energy conversion.

In his concluding remarks, Kelly stated that post-combustion capture is one among several CO_2 capture options, with amine-based absorption being the most technically and commercially mature PCC option. Despite the maturity of amine scrubbing, its commercial deployment faces challenges, and emissions continue to be a significant area of investigation. He noted that other technologies, such as calcium looping, are particularly well-suited for industrial applications like cement manufacturing, while additional methods, including hybrid processes, are still in the research and development phase.

David Miller
National Energy Technology Laboratory

David Miller serves as the Deputy Director and Chief Research Officer (CRO) at the National Energy Technology Laboratory (NETL). Previously, he also served as the Technical Director of the Carbon Capture Simulation Initiative (CCSI), which pioneered new methods to maximise learning and minimise risk during the scale-up process. Additionally, he is a recipient of the Arthur S. Flemming Award for exceptional federal service in applied science and engineering.

In his presentation, David underscored the critical role of carbon capture, utilisation, and storage (CCUS) in achieving net-zero emissions. He highlighted that the Department of Energy's approach to carbon management includes not only the generation of low-carbon energy from sources such as nuclear, geothermal, solar, and wind but also the deployment of CCUS technologies.

David continued by elucidating the mission of the U.S. Carbon Management Lab, which is committed to driving innovation and delivering solutions that contribute to a sustainable and prosperous energy future. The lab's mission is to ensure energy that is affordable, abundant, and reliable, thus fuelling a robust economy and strengthening national security. A pivotal aspect of this mission involves developing technologies aimed at managing carbon across its entire lifecycle and promoting environmental sustainability for all Americans.

He went on to explain that further analysis of decarbonisation costs has revealed that without CCUS, meeting these targets would be extremely challenging, potentially leading to a near doubling of costs. With the Paris Agreement setting even more stringent goals to remain "well below 2 degrees," the significance of CCUS is even more pronounced. David's presentation emphasised not just the necessity of CCUS technologies but also the economic imperative to integrate these solutions into broader climate strategies.

Jerad Bachar
VisitPITTSBURGH

Mr. Jerad Bachar is the President & CEO of VisitPITTSBURGH. Previously, he served as the Executive Director of Investment Promotion, Tourism, Real Estate, Education, and Healthcare for the Bahrain Economic Development Board, a public agency with overall responsibility for attracting inward investment, fostering economic growth, and creating jobs. Jerad in his keynote speech noted that the city, once famed for its steel production, served as an exemplary host for PCCC-7, reflecting its transformation into a centre of innovation and environmental stewardship.

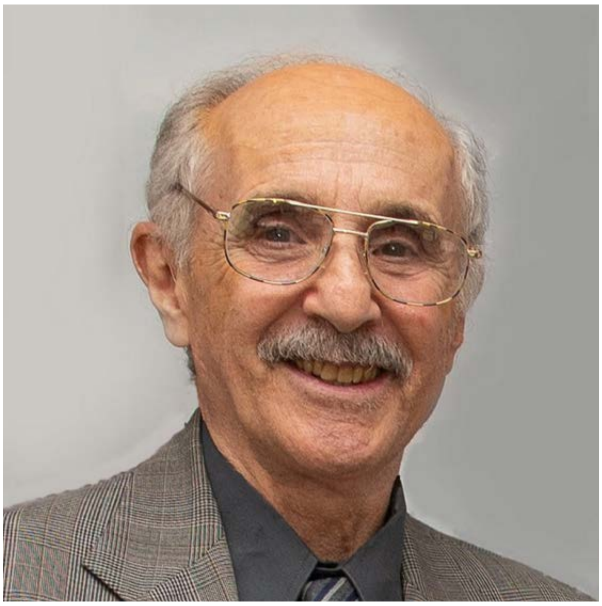
Set against the backdrop of Pittsburgh's renowned skyline, adorned with iconic bridges that symbolise connection and strength, the conference paralleled the collaborative efforts required to combat climate change. The city's narrative of reinvention deeply resonated with the conference's theme of transitioning to sustainable practices. Pittsburgh's evolution from an industrial powerhouse into a leader in green technology and sustainability mirrors the CCUS community's overarching goals to innovate and adapt in pursuit of environmental solutions. The city's dedication to cleaner energy and reduced carbon emissions aligns with the vision of PCCC-7 participants, making Pittsburgh not just a venue, but a living embodiment of the progress and potential at the heart of the conference's discussions.

Sarah Forbes
U.S. Department of Energy

Sarah M. Forbes, who began her career at the NETL working with CCS during the program's formative years, has made significant contributions to the field prior to her current role. Before becoming the Deputy Director for Carbon Management Technologies at the Office of Fossil Energy and Carbon Management, she served as the first Director for CCS at the White House Council on Environmental Quality (CEQ). In this capacity, she was instrumental in the development of U.S., Canadian, and international standards for CCS.

In her compelling presentation on the state of carbon management technology, Sarah highlighted three key messages. The first is a robust affirmation that carbon management technology is effective and vital for achieving our climate goals. The second message emphasises the readiness for commercial scale-up within the U.S., a move that is supported by recent policy advancements. These policies signify a growing recognition of the technology's significance and a commitment to its further development and deployment. This shift indicates a readiness to operationalise CCS at a scale with substantial national impact on emissions.

The third message from Sarah's presentation underlined the need for a holistic approach to fully harness the potential of carbon management technologies. She stressed that further policy development is necessary to create a supportive framework for these technologies, while private investment is crucial for scaling up existing solutions and driving innovation in new carbon capture and utilisation methods. Additionally, she pointed out that international collaboration is essential for sharing best practices, aligning global strategies, and mobilising resources to effectively tackle climate change. By combining these elements, we can unlock the full potential of carbon management technologies, contributing significantly to the global transition to a low-carbon future.



Edward Rubin
Carnegie Mellon University

Edward Rubin, an alumnus and Professor Emeritus of Environmental Engineering and Science at Carnegie Mellon University, as well as a Senior Fellow in the Scott Institute for Energy Innovation, is the most highly cited author worldwide in the field of environmental, economic, and social aspects of CCS. He has been honoured with numerous awards, including the 2020 Dixy Lee Ray Award from the American Society of Mechanical Engineers and the Greenman Award from the IEAGHG in 2022. In his presentation, which focused on the question "Why do we care about cost?", Edward explored the critical role that cost plays in deploying carbon capture solutions. He highlighted that cost is a decisive factor in crucial decisions such as whether to purchase and install a specific capture technology, whether to require or incentivise CCS adoption in certain industries, and whether to invest in R&D for new processes or technologies.

To emphasise the importance of cost considerations in CCS, Edward humorously adopted a format inspired by David Letterman's "Top Ten" lists, presenting 'Ten Ways to Reduce the Estimated Cost of CCS.' This list included:

1. Assuming high plant efficiency.
2. Assuming low fuel and energy costs.
3. Assuming EOR credits for CO_2 utilisation.
4. Assuming a long plant lifetime.
5. Omitting certain capital costs.
6. Reporting costs in earlier year dollars.
7. Reporting costs/tonne of CO_2 based on short tons.
8. Assuming a low interest rate (discount rate).
9. Assuming high plant utilisation (capacity factor).
10. Assuming all of the above.

While presented in a light-hearted manner, this list highlighted the complexities involved in the financial assessment of CCS technologies and the need for realistic assumptions to make CCS economically feasible.

In the conclusion of his presentation, Edward emphasised that policy is the primary barrier to CCS deployment. He stated unequivocally that robust policy is essential to create a market for CCS technologies, which will, in turn, stimulate adoption and drive innovation. Without policies that acknowledge the importance of carbon emission reduction and incentivise CCS, the technology's full potential will remain untapped. Edward's closing remarks were a call to action for the establishment of strong policies that can catalyse the CCS market and facilitate a transition to a more sustainable energy future.

Patricia Scozzafave
Shell Catalysts & Technologies

Patricia Scozzafave serves as the Decarbonisation Consultancy Services Manager at Shell Catalysts & Technologies. She supports a wide range of organisations, from the oil and gas sectors to hard-to-abate industries like cement and steel, developing strategies to help them achieve their decarbonisation goals. Patricia presented Shell's Carbon Capture Learnings, showcasing the company's extensive experience in the development and application of carbon capture technologies.

Patricia highlighted that while selecting the right capture technology is important, a successful CCS project encompasses numerous other dimensions. She pointed out that integration is critical and involves fitting the chosen technology within existing infrastructure. This requires considering pre-treatment needs, integrating with power and utility systems, planning potential tie-ins with existing processes, and managing the compression stage necessary for CO_2 transportation.

She also discussed how the CO_2 is managed post-capture, which includes transportation, whether by pipeline or other means, and the storage solutions, ranging from geological storage to utilisation across various industries. This step is crucial for ensuring efficient operation.

Project management is another fundamental aspect of success. Patricia noted that effective project execution, construction management, and de-risking strategies are essential for timely and on-budget completion of CCS projects. Moreover, she addressed the importance of financing, which involves securing funding support, obtaining necessary approvals, and managing financial risks. Financing is pivotal to a project's capacity to proceed and heavily influences both technology selection and project management decisions.

In conclusion, Patricia emphasised the application of lean engineering principles to streamline processes and reduce waste. She pointed out that integration leads to the optimal combination of process elements, enhancing overall efficiency. Sharper design rules have been implemented, resulting in more cost-effective and reliable systems. Finally, the adoption of standardisation and modularisation has allowed for scalability and repeatability in the manufacturing process, reducing both the initial costs of equipment and the time required for system assembly.

Dan Hancu
U.S. Department of Energy

Dan Hancu, the Division Director for Point Source Carbon Capture at the Office of Fossil Energy and Carbon Management, recently provided an update on the Department of Energy's (DOE) Carbon Management efforts. Boasting over two decades of experience in technical management, techno-economic analysis, and technology scaling from bench to commercial scale, Dan has made significant contributions to the DOE/NETL. His work managing a diverse portfolio of projects in carbon capture and direct air capture technologies has led to the issuance of more than 30 patents and the authorship of 25 peer-reviewed papers. Dan is also a recipient of the Green Chemistry Challenge Award from the US Environmental Protection Agency (EPA) for his work on developing non-fluorous CO_2-philic materials.

In his presentation, Dan focused on the DOE's realignment and the department's strengthened commitment to advancing carbon capture technologies. He highlighted the imperative to reduce carbon footprints across various sectors in the United States, thereby supporting national and global efforts to mitigate climate change.

Dan underscored the strategic deployment of carbon management solutions as essential for reducing industrial emissions. He presented a study detailing the vast potential for mitigating industrial CO_2 emissions through CCUS technologies. The study spanned approximately 2,500 facilities within the U.S. and covered sectors such as refineries, pulp and paper, chemicals, ethanol, iron and steel, cement, natural gas processing, hydrogen, ammonia, and LNG equipment. The study identified sectors like pulp and paper, ethanol, cement, hydrogen, and ammonia as having a high potential for CCUS application, underscoring the technology's role as a critical element in the transition to a sustainable industrial framework.

Additionally, Dan provided insights into the Infrastructure Bill, highlighting the provisions for CCS, including Funding Opportunity Announcements. These announcements are critical for the application and scaling of carbon capture technologies in power generation and industrial operations, showcasing the government's support for CCS as a tool for environmental and energy sustainability.

Takashi Kamijo
Mitsubishi Heavy Industries

Takashi Kamijo joined Mitsubishi Heavy Industries (MHI) in 1993, and since then, he has been a pivotal figure in the realms of process engineering and project management, specifically for chemical plant projects within and beyond Japan's borders. Amassing a wealth of experience spanning three decades in process design, research and development, and management of carbon capture initiatives, Takashi was instrumental in the development of MHI's first commercial venture in Malaysia, and the Petra Nova project, which boasts the largest commercial scale post-combustion carbon capture plant, capturing 4,776 metric tons per day of CO_2.

Takashi's presentation offered an insightful update on the Advanced KM CDR Process™, a technology at the forefront of carbon capture innovation, developed by MHI. Over three decades, MHI has honed this proprietary technology, enabling the capture of up to 98% or more CO_2 from industrial gases, even those with relatively low CO_2 concentrations.

The KM CDR Process™ has more than 70% global market share in capturing carbon from flue gas on a commercial scale. This ease of operation and maintenance, coupled with over 30 years of in-house research, development, and practical experience, has led to MHI's recognition as a leader in the field.

The Advanced KM CDR Process™ is not only a mature and commercially viable technology for various industrial exhaust gases but also represents MHI's commitment to leading the CO_2 capture industry with full-scale solutions. The company's extensive track record in commercial construction within the CCS post-combustion sector is further bolstered by numerous ongoing projects across the world. This includes the plans to use MHI's carbon capture technology on the Drax BECCS Project. As a risk mitigation measure, pilot testing campaigns are routinely employed in the early stages of projects to understand the effects of unknown or trace impurities, ensuring the technology's robustness and reliability in diverse operational environments.

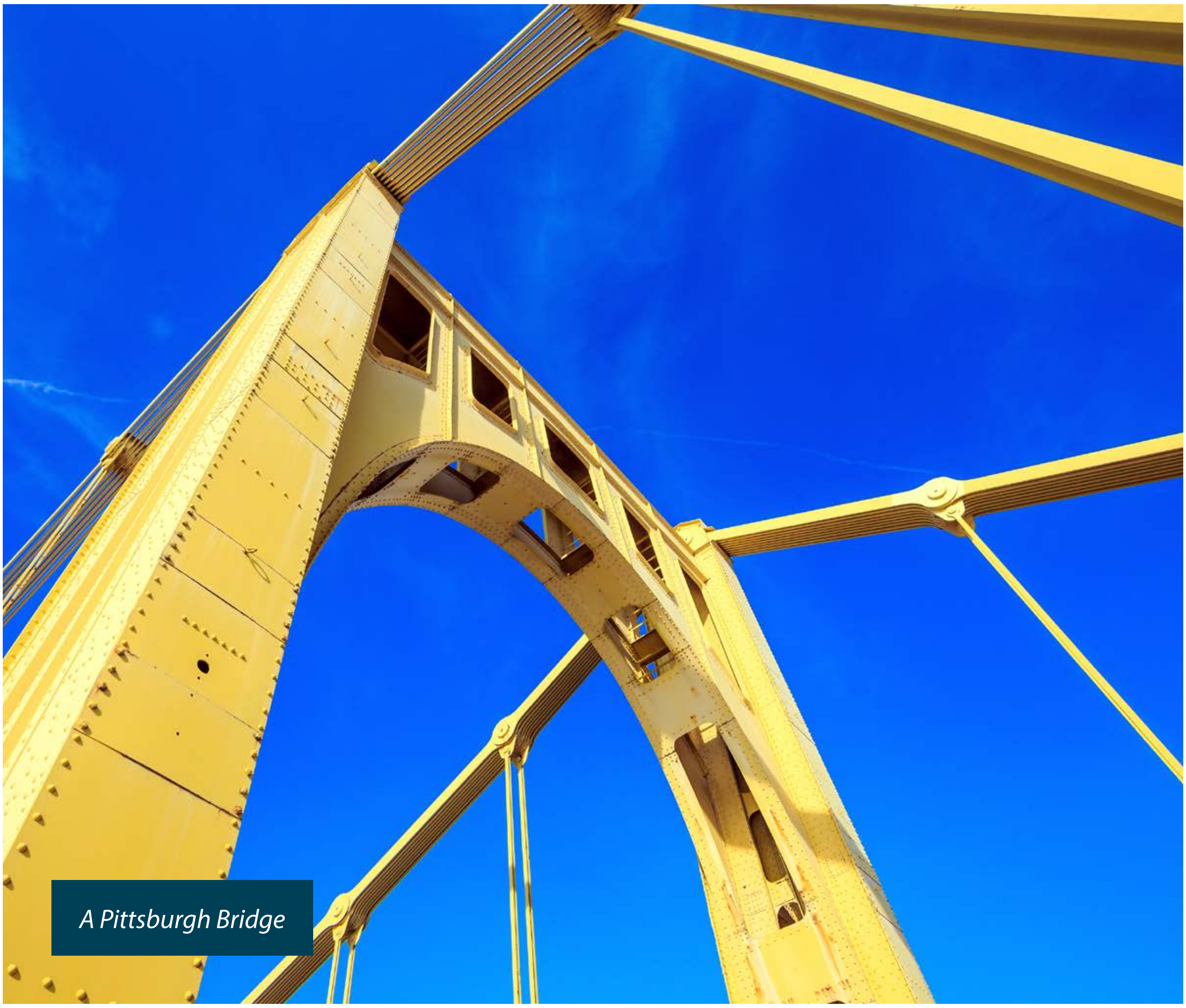
Rob Berra
Worley

Rob Berra, Group Senior Vice President at Worley, leads the CCUS Growth Initiative on a global scale, and is instrumental in cementing Worley's standing within the rapidly expanding CCUS sector. With over 13 years of industry experience with contractors and a major oil company, Rob has steered teams across various domains including engineering, construction, project management, significant P&L operations, as well as in sales and executive management capacities.

In his presentation, Rob highlighted Worley's substantial commitment to CCUS, with the company actively managing 37 CCUS projects, cumulatively aimed at handling 75 million tons of CO_2 per annum. These projects reflect Worley's pledge to support its clients in CCUS endeavours, which includes support for Qatar Energy LNG's decarbonisation objectives through carbon sequestration, and provision of FEED services for a major CCS initiative in Canada.

Worley's expertise is further evidenced by its involvement with the Drax Group's power station. After successfully completing the Pre-FEED phase, Worley is now undertaking the FEED for the first two carbon capture units. The company is also engaged in the VPI Immingham CCUS FEED Project in the UK and is delivering detailed engineering design services for the Kasawari CCS project in Malaysia.

Rob's presentation distilled the essence of efficient project delivery as being fundamental to achieving net-zero ambitions. He stated that the FEED phase is critical in driving towards final investment decisions (FIDs). His emphasis on the necessity of practical experience and in-depth knowledge of CO_2 processes are invaluable assets. Further, he highlighted the importance of forming strategic partnerships with essential suppliers' pre-FID to guarantee project triumph. Concluding his talk, Rob asserted the necessity of having a wide-ranging skill set and a robust tool kit to adeptly manage the intricacies of CCUS project execution.



A Pittsburgh Bridge

Technical Highlights

Credit: MHI

The 7th edition of the PCC conference has been a pivotal platform for advancing our understanding of contemporary challenges and innovations in the field. This year's technical brief is a testament to the ground-breaking research and diverse perspectives presented at the conference. It encapsulates the essence of the technical presentations, each a unique contribution to the evolving landscape of the CCUS field.

The technical reviews that follow not only highlight the cutting-edge developments presented but also contextualise them within the broader narrative of progress and change. In this journey through the technical landscapes of PCCC-7, we aim to provide an insightful overview, reflecting the depth and breadth of expertise that has come to define this esteemed gathering.

The cause of CO_2 emissions can be understood through the Kaya Identity, a formula that breaks down CO_2 emissions into four factors: population, gross domestic product (GDP) per capita, energy use per GDP, and CO_2 emissions per unit of energy consumed. Since it's not feasible to reduce the population or GDP to zero, the focus shifts to reducing the ratio of CO_2 emissions per GDP to zero. This ratio can be further broken down into three components: the amount of fossil fuel used per unit of energy (Fossil/Energy), CO_2 emissions per unit of fossil fuel (CO_2/Fossil), and energy use per unit of GDP (Energy/GDP).

To achieve Net Zero emissions, there are two main strategies:

1. Reducing the fossil/energy ratio to zero, which means completely stopping the use of fossil fuels and conventional methods for producing cement, steel, etc., very rapidly.

2. Reducing the CO_2/fossil ratio to zero, which involves deploying CCS on all fossil fuels used, including direct air capture (DAC), capturing CO_2 from the atmosphere.

These two approaches compete for resources and investment. Both strategies are also supported by reducing the energy/GDP ratio. However, neither approach is easy to implement. Historically, more attention and effort have been directed towards reducing fossil fuel use (Strategy 1.) than deploying CCS technology (Strategy 2.).

The STRETCHER method represents a sophisticated approach to amine post-combustion carbon capture, maximising capture rates while minimising energy requirements

Low lean loadings are essential for high capture rates; accordingly, The STRETCHER (system tuning for regenerator efficiency and target capture with high exit rich) method represents a sophisticated approach to amine post-combustion carbon capture. Its focus on optimising lean loading, balancing lean solvent flow rate, and enabling independent optimisation through solvent storage, all contribute to its ability to maximise capture rates while minimising energy requirements. As the world continues to seek solutions for reducing carbon emissions, particularly in industrial settings, the STRETCHER method offers a promising and efficient avenue for achieving these environmental goals.

Mitsubishi Heavy Industries (MHI) has achieved a significant milestone by demonstrating CO_2 recovery from flue gas using the Advanced KM CDR Process™at Nanko pilot & TCM, achieving an efficiency of ultra-high CO_2 capture rate (99.7-99.8%). This process is particularly notable because it is applied to gases with a relatively low CO_2 concentration, in some cases, the emitted gaseous stream has lower CO_2 concentration than that of atmospheric CO_2. This advancement challenges conventional efficiency benchmarks

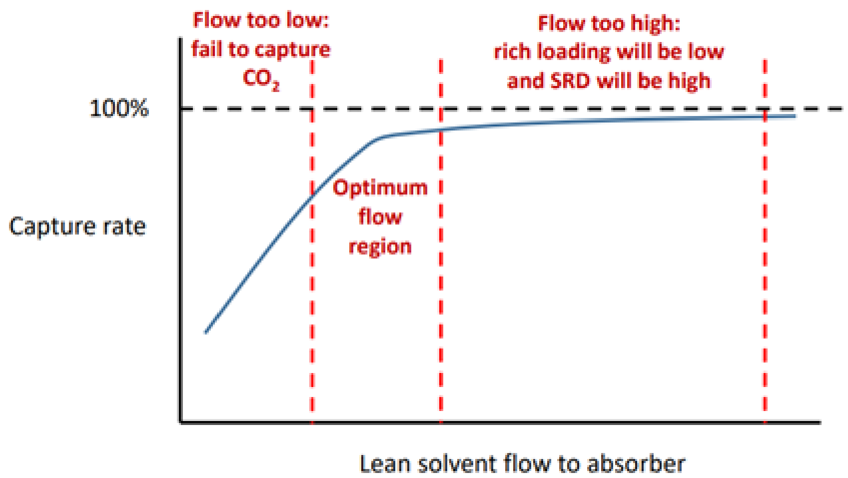


Figure 1. The absorber corner – a 'Goldilocks' problem.

Credit: J. Gibbins, S. Michailos, D. Mullen, M. Akram, M. Lucquiaud. PCCC-7 2023. This figure represents a "Goldilocks" problem because suggests that there is an optimal lean solvent flow rate that maximises CO_2 capture while minimising energy usage and solvent waste. Operating outside of this optimal range either underutilises the solvent's capacity to capture CO_2 or wastes energy by regenerating solvent that is not fully loaded with CO_2.

The significance of achieving CO_2 capture efficiency beyond the 90% threshold was a major focus at PCCC-7. This goal is particularly relevant in the context of net zero emission targets, a point articulated by the Chair of the IEAGHG in his welcoming remarks. The traditional 90% capture rate cap, historically rooted in the economics of capture technology, is increasingly seen as an artificial limit. It does not reflect the full technical potential of current technologies.

and highlights the potential for achieving higher efficiency levels in CO_2 capture technology. However, Techno-economic study indicates that low emission is achieved with a 21% increase in total cost (OPEX+CAPEX) from 90% capture rate in Advanced KM CDR ProcessTM. Increase in CAPEX & OPEX can be minimised through optimal design optimisation. One such approach is the enhancement of the absorber unit by increasing its packing height beyond the base case. Further, findings of the experimental campaigns have indicated that the combination of Advanced KM CDR ProcessTM and KS-21TM solvent shows potential for direct air capture (DAC) application.

The technical presentation on combined cycle power plant with carbon capture, delivered by GE Vernova, underscores the distinction between CO_2 capture and overall GHG emission reduction. It highlights that capturing up to 95% of CO_2

emissions does not necessarily translate to a 95% reduction in total GHG emissions. This emphasises the importance of conducting a rigorous life cycle analysis to accurately account for the total impact on GHG emissions. Once CCS is implemented, the global warming potential (GWP) is predominantly influenced by fuel extraction, processing, and transport, whereas in scenarios without CCS, GWP is mainly driven by plant emissions.

The traditional 90% capture rate cap, historically rooted in the economics of capture technology, is increasingly seen as an artificial limit. It does not reflect the full technical potential of current technologies.

The presentation underscores that the focus should not only be on the percentage of CO_2 captured but also on understanding and minimising the overall GHG footprint.

Given that each power plant possesses unique characteristics, the effectiveness and requirements for CCS integration will vary, necessitating a customised approach for each facility. The role of exhaust gas recirculation was identified as crucial in reducing the flow of flue gas to the CCS system, which can significantly lower the costs associated with CCS.

Furthermore, the presentation addresses a common assumption in the industry or among observers that integrating CCS technology might limit a power plant's ability to meet peak demands. However, it emphasises that this is not necessarily the case. Power plants with CCS are capable of meeting high electricity demands when needed. By efficiently operating during peak times, and maintaining CO_2 capture, these plants can continue to play a vital role in reducing GHG emissions.

This dual benefit of economic gain and environmental protection positions the integration of CCS in power plants as not only a sustainable choice but also a financially viable one. This comprehensive approach underscores the value of CCS integration in enhancing the efficiency and environmental sustainability of power generation.

In the presentation titled "Examination of Factors Affecting the Cost and Performance of NGCC with CCS" by the National Energy Technology Laboratory (NETL), an in-depth analysis was conducted on the various elements influencing the efficiency, output, and costs associated with natural gas combined cycle (NGCC) plants equipped with carbon capture and storage (CCS) technology.

A key aspect examined was the impact of air density on the performance of steam and combustion turbines in NGCC plants. It was noted that a decrease in air density leads to a reduction in the mass throughput of the combustion turbine for a given volume of gas. This reduction, in turn, lowers the power output from the combustion turbine. Furthermore, this decrease in mass flow rate adversely affects the available enthalpy for steam generation, subsequently diminishing the output of the steam turbine. This interplay significantly influences the overall efficiency of the NGCC plant.

Also highlighted were the effects of environmental factors such as humidity and cooling water temperature on plant efficiency. Similar to the impact of air density, these factors can also alter the operational dynamics of the plant, thereby affecting its efficiency.

Capturing up to 95% of CO_2 emissions does not necessarily translate to a 95% reduction in total GHG emissions.

The net power output of NGCC plants, especially with the integration of CCS, is greatly influenced by elevation changes. The presentation underscored that elevation change has the most substantial impact on net plant output due to the derate of the fixed volumetric flow of the combustion turbine. This indicates that plants located at higher elevations might experience a notable decrease in power output efficiency.

As the world progresses towards higher penetration of renewable energy, thermal power plants equipped with carbon capture and storage (CCS) are emerging as vital players in providing low carbon, dispatchable electricity. This transition, while essential, brings to the fore the need for a deep understanding of the potential impact of key process decisions, particularly on the prospects of existing and future fossil fuel-based power generation within a green taxonomy framework.

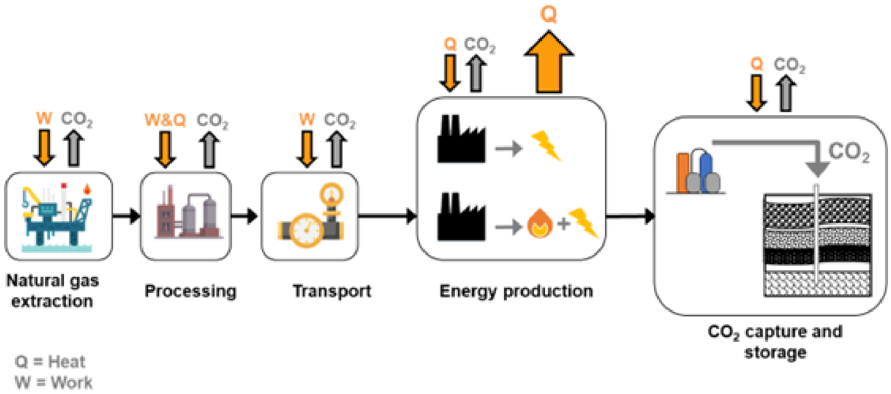


Figure 2. CCS within the context of 'Green Taxonomy.' This figure illustrates how CCGT power plants can fit into a sustainable future as defined by a green taxonomy by reducing their CO_2 intensity. This involves considering the entire lifecycle of natural gas and the operational characteristics of the power plant, including its use of CCS technology and potential transition to blue hydrogen as a fuel source.

Credit: M. Bui, N. Sunny, N. Mac Dowell PCCC-7 2023.

A cost-effective transition to net zero necessitates strategic considerations, especially for natural gas combined cycle gas turbine (NG CCGT) with CCS. Central to this are efforts to reduce methane leakage and achieve high CO_2 capture rates. Additionally, minimising the impacts of start-up and shut down (SUSD) cycles performed by the CCGT-CCS plant is crucial, as these operations can significantly influence the overall efficiency and environmental footprint of the plant.

Another promising development in this realm is the hydrogen-fired CCGT. The main advantage of this technology lies in its ability to maintain SUSD and highly flexible operation without increasing the CO_2 emissions intensity of the electricity generated. However, this approach comes with its own set of challenges. The hydrogen fuel used must be highly carbon efficient to align with the EU taxonomy requirements, ensuring that the overall environmental impact is minimised.

The pursuit of innovative solutions to combat climate change has led to significant advancements in carbon capture technology. One such advancement is the development and engineering-scale testing of a non-aqueous solvent (NAS) for CO_2 capture, as detailed in the presentation titled "Engineering-scale testing of non-aqueous solvent for CO_2 capture at Technology Centre Mongstad."

The journey of NAS technology began with lab-scale development and evaluation between 2010 and 2013. This phase involved solvent screening and small-scale tests, setting the foundation for larger-scale evaluations. Between 2014 and 2016, the technology was advanced at the RTI facility, demonstrating key process features at the bench scale with a capture capacity of 0.11 tons of CO_2 per day. However, the most significant phase began in 2018 with the engineering-scale validation at Technology Centre Mongstad (TCM) in Norway. This phase aimed at pre-commercial demonstration, successfully capturing approximately 220 tons of CO_2 per day. This large-scale testing was critical in evaluating the NAS technology's feasibility for industrial applications.

Throughout these phases, several key metrics were rigorously evaluated. These included the solvent's performance in terms of capture rate, energy requirements, and solvent losses. Operational challenges such as solvent degradation, corrosion, and emissions were addressed. Moreover, a comprehensive techno-economic and environmental, health, and safety (EHS) evaluation was conducted to assess the technology's viability and impact.

As the world progresses towards higher penetration of renewable energy, thermal power plants equipped with carbon capture and storage (CCS) are emerging as vital players in providing low carbon, dispatchable electricity.

The specific challenges faced included resolving technical and process risks, operate TCM plant within emission requirements, minimising absorber temperature increases, and maximising NAS performance with existing hardware limitations. Looking ahead, the NAS technology development path includes exciting ventures that include the FLExible carbon capture and storage (FLECCS) project for dynamic capture from NGCC applications and large pilot testing for cement flue gas capture. These projects aim to enhance process intensification, reduce capital expenses, and further improve solvent chemistry for higher capture rates at lower costs. Additionally, a FEED study is underway for a carbon capture plant in cement manufacturing, targeting a capture capacity of 4000 tons of CO_2/day.

The integration of direct air capture (DAC) with small modular reactors (SMRs) presents an innovative and a viable option to supply heat and electricity to DAC systems. SMRs are characterised by their smaller size, ranging from 10 to 300 MW. Their factory-assembled nature allows for enhanced passive safety features and easier siting compared to traditional large-scale nuclear reactors. This smaller size and modular nature make SMRs a promising option for integration with DAC systems. Two distinct integration designs with different goals were discussed as follows:

High energy integration (HEI) design:

i. Focuses on efficient energy delivery.
ii. Involves a more complex integration process.
iii. Allows for a capture capacity of 0.34 $MtCO_2$ per year per SMR module.

Low energy integration (LEI) design:

i. Results in more energy losses.
ii. Boasts a simpler integration process.
iii. Has a slightly lower capture capacity of 0.32 $MtCO_2$ per year per SMR module.

These designs highlight the trade-off between energy efficiency and complexity in integration. The presentation's key findings shed light on the potential and viability of SMR-powered DAC systems:

• Doubling the Use of nuclear energy: The addition of DAC to SMRs more than doubles the utilisation of available nuclear energy, making this combination a highly efficient energy solution.
• Cost-effectiveness: SMR-DAC systems can remove CO_2 at a lower cost compared to other DAC options. This cost-effectiveness is crucial for the large-scale adoption of carbon capture technologies.
• Scale-up potential: globally, the scale-up potential of SMR-powered DAC systems is significant. These systems could meet the net zero pathways' requirements, presenting a viable solution for large-scale CO_2 removal.

The integration of direct air capture (DAC) with small modular reactors (SMRs) presents an innovative and a viable option to supply heat and electricity to DAC systems.

The UK CCUS (carbon capture, utilisation, and storage) Programme Update presentation illustrates the UK's commitment to advancing CCUS technologies through significant financial investments, innovative business models, and robust policy development. The combination of development funding, capital funding, and revenue funding, along with the detailed business models for industrial carbon capture and hydrogen production, demonstrates a multi-faceted approach to reducing GHG emissions and positions the UK as a leader in CCUS. The key aspects of these funding and business models are as follows:

Development funding:

i. £170 million allocated to the Industrial Decarbonisation Challenge Fund.
ii. A share of £289 million from the Industrial Energy Transformation Fund (IETF) dedicated to CCUS studies.
iii. £19.5 million for the CCUS Innovation 2.0 competition.
iv. Up to £100 million of new R&D funding for direct air capture (DAC) and other Greenhouse Gas Removal (GGR) technologies.

Capital funding:

i. The spring announcement included a significant £20 billion investment, which encompasses:

- o £1 billion CCUS Infrastructure Fund (CIF) for Industrial Carbon Capture, Transport, and Storage projects.
- o £240 million Net Zero Hydrogen Fund for hydrogen projects, not limited to CCUS-enabled hydrogen.
- o A portion of the £289 million IETF for on-site carbon capture investments.

ii. Policy development for the deployment of bioenergy with carbon capture and storage (BECCS) and GGRs is also ongoing.

Revenue funding:

i. The dispatchable power agreement for power CCUS projects.
ii. The industrial decarbonisation and hydrogen revenue support scheme to fund business models for low-carbon hydrogen production and industrial carbon capture.
iii. Continued policy development for the deployment of BECCS and GGRs.

The presentation delves into specific business models for industrial carbon capture and hydrogen production:

Industrial carbon capture business model:

i. This model includes a private law contract of up to 15 years (the 'ICC Contract') that provides payment per tonne of captured CO_2. This payment is intended to cover operational expenses, transport and storage (T&S) charges, and repayment of, and a return on, capital investment in carbon capture equipment.

ii. Capital grant co-funding is also available for a portion of the capital cost of capture projects, intended for initial projects to mitigate certain risks.

iii. The contract will be funded via revenue support from the exchequer through the IDHRS scheme and the capex co-funding via the CCS Infrastructure Fund (CIF).

Hydrogen production business model:

i. Producers will be paid a premium for low carbon hydrogen produced and sold, calculated as the difference between the strike price and the reference price.
ii. The model seeks to incentivise the production and use of hydrogen.
iii. The reference price is designed to reflect the hydrogen market price and, in the absence of a market benchmark, is the higher of the natural gas price floor and the achieved sales price, with a price discovery incentive (PDI).
iv. The PDI, separate from the difference amount, is intended to incentivise the sale of hydrogen above the Floor Price.

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growing interest in mobile, small scale, and modular carbon capture technologies, particularly for legacy internal combustion engines, signifies the broadening application of carbon capture in efforts to reduce transportation emissions. This field has seen active engagement from companies like Aramco, Remora, MHI, OGCI/ Stena Bulk, TNO/Conoship, GCMD, PMW, and Carbon Clean, who are at the forefront of developing and implementing these innovative solutions.

Figure 3. Illustration of an on-board modular capture system

Credit: J. Oh, D Kim, S. Roussanaly, R. Anantharaman, Y Lim, PCCC-7 2023.

The exploration into carbon capture technologies encompasses both pre-combustion and post-combustion concepts, each presenting unique cost profiles and efficiencies. In pre-combustion systems, where components like methanol reformers and fuel cells are utilised, the bulk of the cost is attributed to the power-train, with storage tanks being the most expensive part. These systems, while offering reasonable to low carbon capture rates, face major cost implications in the solvent and CO_2 compressor areas. Conversely, post-combustion systems, despite having lower initial solvent costs, contend with additional operational expenses such as fuel and tank maintenance, and the compressor remains a significant cost factor. These systems are characterised by lower capture rates, higher specific heat and work requirements, but offer the advantage of lower upfront and avoidance costs.

The initial financial assessment of both pre-combustion and post-combustion concepts suggests that their overall costs are manageable when considered in the context of total vehicle ownership and operation.

The study titled "Optimal Process Configurations of MEA-based On-board Carbon Capture for Flexible Ship Operation" embarked on the assessment to identify the most efficient capacity and configuration for amine-based carbon capture systems on-board ships. The primary objective of the study was to determine the optimal size and setup of these systems, ensuring they are neither oversized nor entail unwarranted capital investments, while also accurately reflecting the realistic load profiles of marine engines.

The study also emphasised the need to consider realistic operational patterns of marine engines, which often fluctuate and do not always run at full capacity. The findings of the study and its implications for future research are particularly insightful. It was observed that the performance of amine-based on-board carbon capture systems varied under different exhaust gas conditions, closely mirroring a realistic sailing profile. In terms of optimal capacity, it was found that smaller systems could achieve a comparable level of CO_2 reduction (56% – 59%) while also reducing capture costs to €232–235/ton. This finding is significant as it positions on-board carbon capture systems as more cost-competitive compared to alternatives like biofuel, which stands at €304/ton.

Furthermore, when considering multiple columns within the system, the use of two small absorbers was shown to achieve a higher CO_2 avoided rate (64%) without incurring additional avoidance costs. This result indicates that there is merit in exploring configurations that involve multiple smaller units rather than a single large one.

Looking forward, the study suggests further exploration into scenarios where the average main engine load is relatively low, such as at 30% and 40%. This area of research is crucial because ships often operate at these lower load levels. Additionally, the study advocates for the exploration of novel configurations to further enhance the carbon reduction potential of these systems.

The growing interest in mobile, small scale, and modular carbon capture technologies, particularly for legacy internal combustion engines, signifies the broadening application of carbon capture in efforts to reduce transportation emissions.

The Wyoming Integrated Test Centre is at the forefront of carbon capture technology, embarking on an ambitious project that involves the implementation of a large-scale membrane pilot and novel solid adsorbent CO_2 capture technology. The Membrane Technology Research is development a 150 tonne /day capture rate system, which will be housed in the large test bay at the Wyoming Integrated Test Centre and poised to become the largest CO_2 capture project using membrane technology in the world. This project, with a substantial total cost of approximately $70 million, aims to achieve a remarkable 90% CO_2 capture rate. This represents a monumental leap in the capabilities of membrane technology in carbon capture. Moreover, a key advantage of this technology is its potential to operate with close to net zero water consumption, addressing one of the critical environmental concerns associated with such projects.

Compact Membrane Systems presented data on their research into facilitated transport membranes (FTMs). They reported that FTMs show promise for capturing hard-to-abate streams. The ease of use requiring fully electric process, no steam, solvents, or regeneration, along with a modular approach and resistance to degradations from gaseous species such as SOx, NOx, and H_2S, makes these membranes attractive both economically and in terms of efficiency.

However, while the prospects are promising, it is important to acknowledge the inherent challenges associated with this technology, particularly when it comes to increasing the capture rate. Elevating the capture rate from 90% to 99% presents a significant hurdle, due to the complex dynamics of membrane capture technology. Achieving such high efficiency in CO_2 capture is a formidable task that may encounter limitations in current technological capabilities. Lower feed concentrations in gas streams also pose significant design challenges for membrane-based capture systems, requiring careful consideration of selectivity, processing volume, efficiency, and cost.

The presentation on environment permitting, focusing on U.S. regulatory considerations for carbon capture, utilisation, and storage (CCUS), provided crucial insights into the strategic planning required for successful CCUS project implementation. The key points from the presentation emphasised the importance of thorough preparation and proactive strategies in navigating the complex permitting process in the United States.

A vital consideration is the importance of discussing potential emissions with technology providers at an early stage. This dialogue is crucial as it helps in understanding the specific emission profiles associated with different CCUS technologies.

First and foremost, the presentation highlighted the necessity of investing significantly more time in the permitting evaluation during the feasibility studies of CCUS projects. This step is essential in determining the most suitable permitting approach. Early and detailed evaluation in the feasibility phase allows project developers to identify potential regulatory challenges and requirements, thereby aligning the project's objectives with regulatory expectations. This proactive approach in the initial stages is instrumental in streamlining the permitting process later on.

A vital consideration is the importance of discussing potential emissions with technology providers at an early stage. This dialogue is crucial as it helps in understanding the specific emission profiles associated with different CCUS technologies. Early discussions can guide the selection of appropriate technology and also inform the permitting strategy, particularly in meeting environmental compliance and regulatory standards. Understanding emissions in detail ensures that technology choices are aligned with regulatory requirements, thus mitigating risks of non-compliance and potential delays.

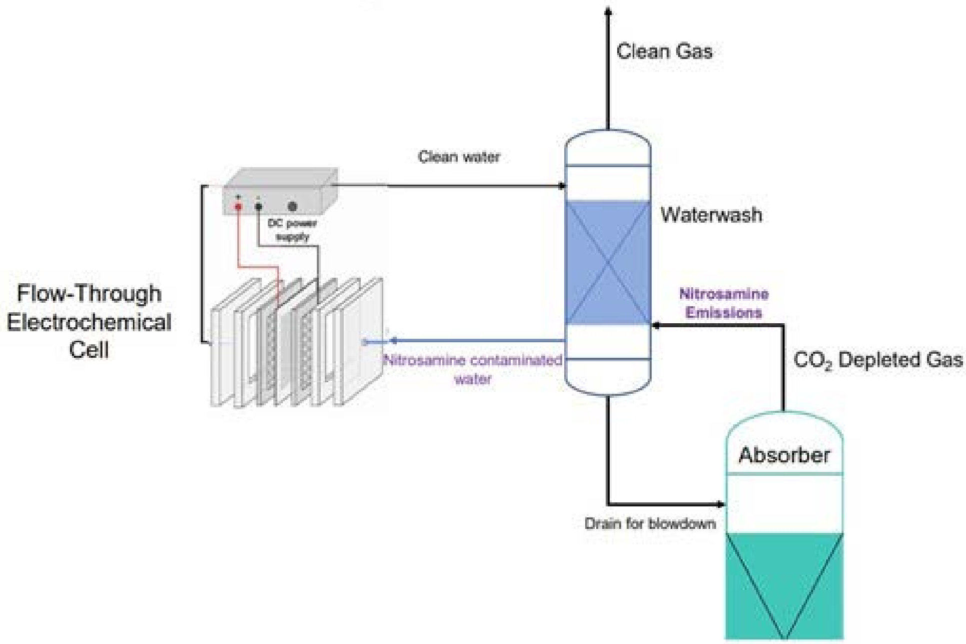

Figure 4. Electrochemical decomposition of Nitrosamine. outlines a process designed to reduce nitrosamine levels within a carbon capture system via electrochemical decomposition. The DC power supply provides the necessary current to drive the electrochemical reactions that reduce nitrosamines in the contaminated stream. Results shows approximately 99% of nitrosamines decomposed. Credit: K. Abad, S. Bhatnagar, K. Liu, J. Thompson. PCCC-7 2023.

Lastly, the presentation underscored the importance of beginning the permitting process as early as possible. Allowing room in the project time line for such setbacks is crucial. Early initiation of the permitting process provides a buffer against delays and ensures that the project can adhere to its planned schedule. It also allows for sufficient time to address any issues that may arise during the permitting process, including additional data requirements, public consultations, or environmental assessments.

The cement industry faces the significant challenge of deep decarbonisation. Among the various strategies being explored, CCS technologies, specifically post-combustion carbon capture and storage (PCCCS) and direct air carbon capture and storage (DACCS), have emerged as promising solutions. These technologies offer a pathway to significantly reduce the carbon footprint of cement production, a process traditionally known for its high CO_2 emissions.

However, the integration of PCCCS alone may not be sufficient to completely decarbonise the cement sector. While PCCCS effectively captures CO_2 emissions from the cement manufacturing process, it does not address emissions from other sources. This is where "CO_2 negative" technologies like DACCS or bioenergy with carbon capture

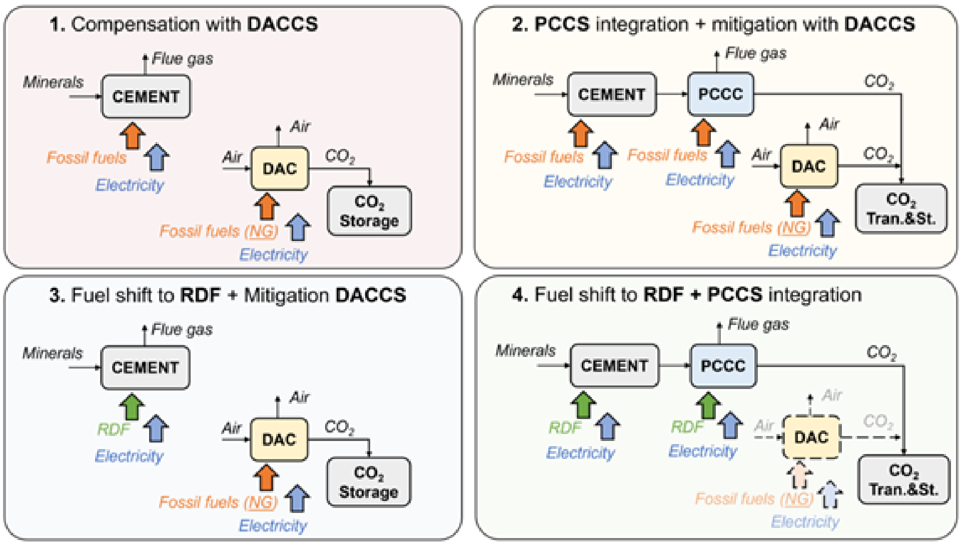

Figure 5. Cement industry net-zero CO_2 decarbonisation pathways based on carbon capture and waste fuels integration. These strategies aim to reduce the carbon emissions of cement production, aligned with global climate goals, and potentially create a circular economy by utilising waste and capturing CO_2 for use in other applications.

Credit: D. Ferrario, T. Pröll, S. Stendardo, A. Lanzini. PCCC-7 2023.

and storage (BECCS) become crucial. These technologies have the potential to capture more CO_2 than is emitted during the production process.

Another critical component in the decarbonisation strategy is the shift to alternative fuels, such as waste-derived fuels like Refuse-Derived Fuel (RDF). Switching to these alternative fuels presents an energy and cost-efficient solution to reduce CO_2 emissions from the cement sector. The use of RDF, for instance, could lead to a CO_2 emissions reduction of approximately 10-20%. This reduction is significant, considering the large scale of emissions typically associated with cement production.

The most effective approach, however, may be a combination of these strategies. By integrating a fuel switch to RDF with PCCCS technology, the cement industry could potentially achieve a net-zero or even carbon-negative process. This combination offers a dual benefit: RDF reduces the initial amount of CO_2 generated, while PCCCS captures and stores the remaining emissions. This synergistic approach represents a comprehensive solution for deeply decarbonising the cement industry, aligning it with global efforts to combat climate change and achieve a sustainable future.

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Technical Visit

On 28 September 2023, 40 delegates were treated to a guided tour of NETL, offering them a first-hand glimpse into the state-of-the-art facilities and R&D initiatives at NETL, which, over the last century, has pioneered breakthroughs in energy research and technology in response to the nation's evolving energy needs.

A safety briefing was conducted for delegates en route to the NETL facilities. Upon arrival, delegates were briefed on the laboratory's mission and provided with a broad overview of the research programmes undertaken at both NETL and its affiliated facilities.

Firstly, a technical briefing was provided on the Carbon Capture Simulation for Industry Impact (CCSI2). CCSI2 develops, validates, and applies advanced computational techniques for technology simulation, optimisation, uncertainty quantification (UQ), and process control. CCSI2 with the aim to provide a fundamental and interdependent understanding of CO_2 capture material-, device-, and system-level performance leading to more informed R&D guidance on CO_2 capture technology development and reduced risks during commercialisation. This project is led by NETL in partnership with Lawrence Livermore National Laboratory (LLNL), Lawrence Berkeley National Laboratory (LBNL), Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), West Virginia University, and the University of Texas at Austin.

At NETL, delegates visited the Catalytic Carbon Conversion Laboratory, which is dedicated to researching, developing, and demonstrating a wide range of technologies that transform CO_2 into environmentally friendly, equitable, and economically valuable products. This initiative is instrumental in fostering low-carbon supply chains, contributing to the goal of achieving a decarbonised economy by 2050. Although various methods for CO_2 transformation exist, including biological uptake and mineralisation,

NETL Site Visit

this laboratory primarily focuses on catalytic conversion. They are now exploring innovative methods, such as multifunctional nano catalysis and process-intensified conversion systems. The range of products resulting from these processes includes building materials, agricultural products, polymers, chemicals, and fuels, among others, all providing tangible benefits. The program targets anthropogenic carbon oxides from sources like power generation, industrial processes, and direct air capture of CO_2. The products derived from these processes can generate revenue for both the emitter and the user of the CO_2. This revenue can offset the costs associated with CO_2 capture, treatment, and transportation, while simultaneously contributing to a net decrease in CO_2 emissions released into the atmosphere.

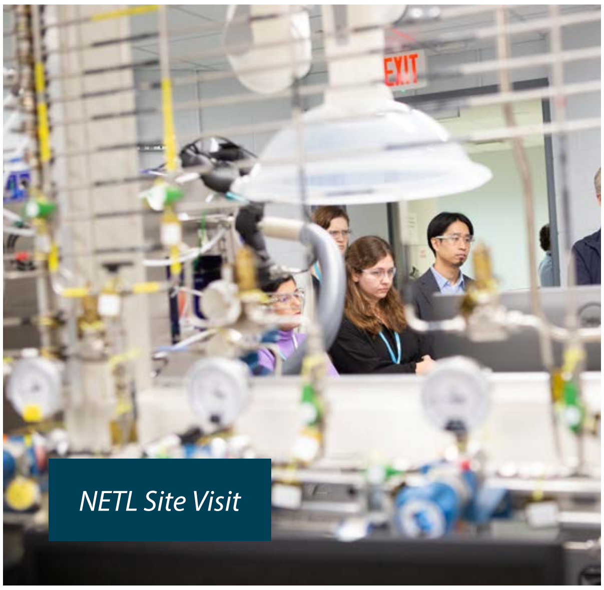
Delegates were taken on a tour of the NETL DAC Centre, commencing tests in 2023, the specialised facility's objective is to facilitate the market readiness of cutting-edge DAC technologies that are both technically sound and economically feasible. The Centre provides universities, research institutions, and businesses developing DAC technologies with access to its extensive facilities and expertise. It offers inclusive, state-of-the-art testing facilities, along with the opportunity for collaborative access to NETL's world-class expertise. The Centre also provides both standardised and bespoke testing options, recognised as the "gold standard" in technology validation.

The Centre boast an array of capabilities spanning from lab scale to small pilot scale, each designed to facilitate the advancement of DAC technologies at various stages of development. At the lab scale, the focus is on novel material assessment, handling approximately 0.1 kg of CO_2 per day. This includes systems for mixed-gas measurements with sample sizes greater than typical lab scales and the ability to accommodate all common materials such as powder, granular, fibre, and structured forms. These systems are automated for extended, multi-cycle testing, emphasising material properties and longevity.

Moving up to bench scale, the centre offer test beds with flexible reactor designs capable of processing around 4 kg of CO_2 per day. These are sized for modules at a typical scale of 12" X 12" X 12" and can accommodate common form factors including granular solid, fibre mat, or monolith. Instrumentation at this level is focused on module capture and flow measurements, providing vital data for prototyping models.

At the small pilot scale, the centres feature bays for evaluating developer-built DAC skids, handling approximately 30 kg of CO_2 per day. These are tailored for testing small pilot scale prototype DAC units under conditions representative of various climates and are automated for extended, multi-cycle testing. The instrumentation here is geared towards measurement of all parameters needed for the assessment of field deployment at locations like the NCCC or a DAC hub, accommodating a wide variety of technology types.

The site visit concluded with delegates reflecting on and discussing their experiences over lunch break.



NETL Site Visit

Side Events & Networking

On the eve of PCCC-7, the Station Square Sheraton buzzed with excitement as its Reflections Room opened its doors for the welcome reception of a much-anticipated conference.

The ambience was electric yet welcoming, as delegates from various corners of the globe gathered, exchanging greetings and business cards in the warm glow of the room's soft lighting. The Reflections Room, aptly named for its mirrored decor reflecting the diverse assemblage of academia and industry, served as a melting pot of ideas and aspirations. Laughter and conversation ebbed and flowed, as attendees networked and built camaraderie, setting the stage for the collaborative spirit that would characterise the coming days of the conference.

As dawn broke into the first day and on the side of the technical sessions, the break lounge transformed into a vibrant hub of intellectual exchange during breaks and the scheduled poster session. Delegates navigated through the carefully arranged displays, engaging with the innovative research and cutting-edge developments showcased on each poster. The informal setting, punctuated by the clinking of coffee cups and the rustle of pastries, allowed for a fluid exchange of insights and constructive critique. This environment of shared knowledge continued into the evening of the second day, where the Reflections Room once again played host, this time to the conference dinner. With the Pittsburgh skyline painted in the hues of the setting sun and the Monongahela River flowing quietly by, the room was abuzz with anticipation. It was here, amid the stunning backdrop and convivial atmosphere, that the CCS community present took a moment to formally recognise and honour Ed Rubin for his illustrious career, as he transitioned to the status of Emeritus and acknowledging not just his past achievements but also for the legacy he would continue to build in the new chapter of his journey.

Networking and the Gala Dinner

Where are we now?

The International Energy Agency, the Intergovernmental Panel on Climate Change, and other authoritative bodies consistently suggest that meeting global climate goals necessitates reaching annual CO_2 storage rates of around 1 Gt/annum by 2030, and this figure needs to increase to about 10 Gt/annum by 2050. Though the development of CCS projects is picking up the pace, only about 41 projects with a capacity of almost 50 Mtpa CO_2 are operational, signifying about 13% of projects in development, construction, and operation in 2022. To mitigate climate change and achieve net-zero emissions, CCS, and carbon dioxide removal (CDR) must be scaled up to the level of gigatons annually.

Bridging the gap between the present state of CCS deployment and the ambitious targets set by global authorities requires an acceleration of both technology and policy. The PCC conference has served as a beacon, highlighting the technological innovation and policy frameworks necessary to enhance the scalability of CCS solutions. Acknowledging the current operational capacity of CCS projects, the focus now intensifies on bridging the vast divide to reach the gigatonne scale mandated by 2030 and beyond. This pivotal shift necessitates a concerted effort across industries, governments, and societies to embrace the urgency of climate action. The dialogue and revelations from the PCC conference have not only reaffirmed our commitment but also charted a path forward that harnesses collective wisdom to advance CCS technologies. This transition, underscored by the conference, lays down the challenge of turning understanding into action, and ambition into reality, setting a course towards a more resilient and sustainable future.

The conference has illuminated the contemporary challenges we face and the innovative strides we are making towards overcoming them. With a clear understanding of the Kaya Identity, we recognise the immutability of certain factors like population and GDP growth. Therefore, our collective endeavours have shifted towards refining the ratios of CO_2 emissions per unit of GDP and energy use per unit of GDP, with a keen focus on reducing the carbon intensity of fossil fuels and enhancing energy efficiency. The discussions and technical reviews presented at the conference have established a robust foundation for the next phase of evolution in the CCUS landscape.

Looking ahead, the quest for net zero emissions continues to navigate the intricate balance between reducing fossil fuel dependency and maximising the deployment of CCS technologies. The innovative STRETCHER method, along with success in ultra-high CO_2 recovery and the insightful presentations from the industry, research organisations and the academia, have provided us with a blueprint for optimising CCS integration and achieving greater efficiency. Moreover, the commitment to advancing CCUS through comprehensive funding and innovative business models especially in the North America and Europe paves the way for a ripple effect across the global in this realm. The exploration into non-aqueous solvents, the potential of integrating direct air capture with small modular reactors, and the advancements in mobile carbon capture technologies further underscore the dynamic and multifaceted nature of our progress. As we move forward, the integration of these technologies, along with complementary strategies such as alternative fuels and RDF, will be pivotal in achieving the deep decarbonisation of industries. The collaborative spirit of the PCC conference is continually setting the stage for a transformative era in carbon management, one that promises to usher in a more sustainable and environmentally conscious future.

A flavour of PCCC-7

Save the Date

The Greenhouse Gas Control Technologies (GHGT) Series is the world's foremost conference in the field of carbon capture and storage.

GHGT provides an opportunity for researchers, industry professionals and policymakers to share their knowledge and experience.

Featuring over a hundred expert speakers from across the globe, GHGT gives you the opportunity to hear from thought leaders on a huge range of topics related to CCS including: Carbon Capture, Transportation, Storage, Utilisation, Monitoring and many more.

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