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IEAGHG

IEAGHG workshop on comparative techno-economic assessment of commercially available CO_2 conditioning technologies.

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IEA Greenhouse Gas R&D Programme

About the IEA Greenhouse Gas R&D Programme

Leading the way to net zero with advanced CCS research. IEAGHG 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.

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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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Glossary

Acronyms

BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization, and Storage
DAC	Direct Air Capture
DORA	Dissolved Oxygen Removal Apparatus
EOR	Enhanced Oil Recovery
FCC	Fluid Catalytic Cracking
Ktpa	Kilotons per Annum
LP	Low Pressure
MMscfd	Million Standard Cubic Feet per Day
MeDORA	Membrane-assisted Dissolved Oxygen Removal from Amine solution for CO_2 capture
MetCCUS	Metrology Support for Carbon Capture Utilisation and Storage
OPEX	Operational Expenditure
T&S	Transport and Storage
TEG	Triethylene Glycol
TRL	Technology Readiness Level

Chemical Formulas

CO	Carbon Monoxide
CO_2	Carbon Dioxide
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulphide
HAP	Hazardous Air Pollutants
Hg	Mercury
N_2	Nitrogen
NOx	Nitrogen Oxides
O_2	Oxygen
PM	Particulate Matter
SO_2	Sulphur Dioxide
SOx	Sulphur Oxides
VOC	Volatile Organic Compounds
barg	Bar Gauge
ppm mol	Parts per Million by Mole
ppmv	Parts per Million by Volume

Executive Summary

IEAGHG organized a virtual expert workshop titled 'Comparative Techno-economic Assessment of Commercially Available CO_2 Conditioning Technologies' on the 20th of February 2024. The workshop aimed to facilitate the exchange of knowledge and insights among a panel of international experts on CO_2 conditioning, with the goal of informing the scope of a technical specification for a comprehensive IEAGHG report. This report synthesises the presentations and discussions from the workshop.

As the CCUS landscape evolves, conditioning CO_2 captured from both industrial processes and the power sector introduces new challenges due to the presence of diverse impurities dictated by the type of fuel, feedstock, capture media, and process conditions. The workshop emphasized the critical importance of selecting appropriate conditioning strategies, pivotal in shaping the industry's infrastructure, operational efficiency, safety, and economic outlook.

The key themes of the workshop included the essential nature of accurately measuring these impurities, underscoring the vital role of metrology in ensuring the reliability and efficacy of CCUS technologies. The absence of a universal CO_2 stream specification was identified as a significant barrier to standardization across the CCS value chain. The workshop underscored the urgent need for a Europe-wide CO_2 specification to ensure consistency and safety throughout CCS operations, facilitating smoother transitions between emission, transportation, and injection/utilization stages. Recent technical insights on the corrosive potential of CO_2 streams, especially those with high levels of NOx and other impurities, were discussed. These findings have led to a reassessment of permissible NOx levels and highlight the need for upstream improvements to enhance CO_2 capture and conditioning processes. The economic implications of purifying CO_2 for use in CCU were underscored, a subject critical yet underrepresented in current literature. The need for CO_2 in CCU applications introduces a complex landscape of purity requirements distinct from those found in traditional transport and storage (T&S) scenarios. Identifying a co-conditioning strategy is crucial, as it might dictate the choice of technology due to its ability to eliminate multiple contaminants simultaneously. This underscores the importance of adopting a holistic approach in selecting the most cost-effective and efficient purification method.

The workshop also laid bare an often-overlooked topic in CO_2 conditioning: the waste streams that may emanate from the conditioning process. It explored what to do with this waste, how to dispose of it, the cost implications of disposal, and the associated life cycle emissions.

The IEAGHG's virtual expert workshop on 'Comparative Techno-economic Assessment of Commercially Available CO_2 Conditioning Technologies' highlighted the complex and evolving landscape of CO_2 conditioning in CCUS. By gathering a diverse group of international subject matter experts, the workshop not only facilitated a rich exchange of

knowledge and insights but also critically addressed the multifaceted challenges presented by impurities in CO_2 streams. The discussions underscored the necessity of precise impurity measurement, the development of a universal CO_2 specification, and the strategic selection of conditioning technologies to meet these challenges head-on. Moreover, the workshop brought to the forefront the economic and environmental considerations of CO_2 purification and the pressing need to manage waste streams effectively. As the CCS and CCU fields continue to advance, the insights gained from this workshop is expected to play a pivotal role in shaping future strategies, ensuring that they are both effective in mitigating pollutants present in CO_2 stream and viable from a technical and economic perspective.

Purpose Statement

By convening a group of subject matter experts (SMEs) from academia, industry, and research-based organizations, this workshop aims to provide formative insights and data that will inform the development of a technical specification for a study focused on 'An In-Depth Cost Evaluation of Commercially Available CO_2 Conditioning Technologies'.

Introduction

Impurities in CO_2 streams captured from point sources can originate via a broad spectrum of mechanisms, significantly impacting the efficiency and cost-effectiveness of CO_2 transport and storage (T&S). For instance, sulphur compounds and nitrogen oxides may originate from the combustion of fossil fuels, while water vapor, often a by-product of combustion, triggers the formation of compounds in the gas phase that may remain as impurities in the captured and compressed CO_2. The oxidizing agent used for combustion, such as air, can also introduce impurities like nitrogen, oxygen, and argon. Further, the materials and chemicals used in the CO_2 separation process, and their degradation products, can be carried over into the CO_2 stream, adding another layer of impurities. These impurities may have to be removed to prevent corrosion, hydrate formation, dry ice formation or because of other reasons such as high operating costs.

The presence of these impurities necessitates advanced conditioning technologies to purify CO_2 streams before T&S, ensuring compliance with regulatory standards and the operational integrity of T&S infrastructure. Further, the variability and concentration of these impurities can significantly influence the selection, design, and economic feasibility of CO_2 conditioning technologies, underscoring the importance of a comprehensive technoeconomic assessment to identify the most effective and cost-efficient solutions for CO_2 purification.

Several European CO_2 T&S hub projects, such as Aramis and Porthos in the Netherlands, those operated by Fluxys in Belgium, and Longship in Norway, have made their CO_2 purity criteria public. These criteria specify limits for over twenty different chemical species, including water, with some of the limits being in the parts per million by mole (ppm mol) range. To adhere to these T&S hub CO_2 specifications, CO_2 emitting entities might be compelled to implement specialized CO_2 conditioning processes. Currently, technologies for removing water are the only ones fully established, and the costs for dehydration units have been assessed. However, for other impurities, there has been a relatively limited exploration of possible removal technologies, particularly regarding their performance constraints and associated costs.

Consequently, CO_2 emitters must now consider the additional financial burden imposed by the need to align their CO_2 streams with the strict purity specifications set by these T&S hubs, potentially increasing the overall cost of compliance and impacting the economic feasibility of their operations.

Technical Discourse

Session 1: Keynote Remarks by Dr Owain Tucker, Shell

In his keynote remarks, Owain Tucker of Shell underscored the significance of CO_2 quality, in the realm of CCS. Highlighting Shell's extensive experience in CO_2 transport and storage, and the construction of CO_2 pipelines, Tucker pointed to the Quest CCS project as an exemplary case where CO_2 has been successfully captured from hydrogen production, conditioned, transported, and stored in Alberta since 2015, showcasing Shell's standing in this field.

Owain highlighted a case in the United States where CO2, sourced from the subsurface and devoid of oxygen, is dried and transported across thousands of miles in carbon steel pipelines, with the CO2 limitedly corrosive. In contrast, a UK pipeline over 100 miles long, which previously transported a mixture of natural gas, hydrogen sulphide, water, and CO_2 from the decommissioned Miller field to the St. Fergus gas plant near Peterhead, Scotland, was constructed from corrosion-resistant alloys. This difference illustrates how the specific composition of the transported gases dictates the choice of materials. In the US, the approach of dehydrating and conditioning CO_2 from subsurface sources, followed by its transport via low-cost carbon steel pipelines, is considered the economically optimal solution.

In the evolving CCS landscape, Owain highlighted the new challenges presented by the capture of CO_2 from industrial processes, which contain diverse impurities such as oxygen, sulphur dioxide, and nitrogen dioxide. One approach is to condition the CO_2 directly at the manufacturing plant, removing contaminants before they enter the transportation system. This method addresses smaller CO_2 volumes and allows for the potential management of the waste stream at the point of capture, though it presents limited economies of scale. An alternative strategy involves establishing a gathering network to collect contaminated or impure CO_2 streams, conditioning them prior to their entry into major trunk lines. While this approach accommodates much larger volumes of CO_2, diluting the contaminants more effectively and offering greater economies of scale, it also introduces complex challenges related to the management of the resulting waste stream. Consequently, the industry faces critical decisions regarding where and how to best condition CO_2; whether at the source or by consolidating streams at a centralised hub.

Owain stressed the importance of choosing conditioning strategies wisely, as these decisions will shape the industry's infrastructure and its operational, safety, and economic outlook. It is imperative to understand available technologies, their costs, and their impact on safety and operability forms the foundation of developing optimal CCS solutions. Dr Tucker's address not only highlighted the complex considerations involved in CO_2 conditioning but also positioned the workshop as a vital step toward expanding the collective knowledge base, crucial for advancing CCS as a component of the global path to net zero.

Session 2: Metrological analysis of impurity levels in CO_2 captured by Iris de Krom, VSL National Metrology Institute

How can we assess the impurities in the CO_2 stream and guarantee the reliability of our technologies? Iris de Krom's enlightening presentation on the Metrology Support for Carbon Capture Utilization and Storage (MetCCUS) project offers a comprehensive look into how metrology, the science of measurement, plays a pivotal role in the development of CCUS technologies.

Iris de Krom began by providing insight into the MetCCUS project, which is funded by the European Partnership on Metrology and co-financed by the European Union Horizon Europe Research and Innovation Programme and from the Participating States. The project aims to develop metrologically sound reference materials, measurement and calibration methods, and infrastructure necessary to obtain reliable measurement results, comply with specifications and offering crucial insights into the metrological challenges facing the CCUS industry in Europe. This focus ensures the efficient and safe implementation of CCUS technologies.

Iris's presentation highlighted several measurement challenges critical to the advancement of CCUS technologies, including accurate flow measurement, reliable emissions monitoring, and precise chemical analysis required to determine the purity and composition of captured CO_2. Understanding CO_2's physical properties under various conditions is also crucial for the safe and efficient operation of CCUS technologies.

The MetCCUS project is undertaking significant initiatives to overcome these challenges, the remainder of Iris's presentation focused on the following:

The development of primary reference materials with impurities in CO_2, crucial for calibration. Ensuring that measurements of CO_2 purity and impurity levels are accurate, reliable, and consistent across different contexts is essential for the efficacy of carbon capture processes and adherence to specifications and regulatory standards for utilization and storage.

Enhancement of Sampling Methods: The project is also dedicated to improving sampling methods and ensuring material comparability. The ability to accurately sample CO_2 and analyse these samples in various scenarios is foundational for evaluating CCUS technologies' effectiveness. Standardized methods for sampling are being developed, laying the groundwork for a globally unified approach to CO_2 measurement.

Advancements in Measurement Techniques: Recognizing the critical importance of precise CO_2 composition measurement, MetCCUS is pioneering both online and offline measurement methods. Online methods offer essential real-time data for immediate CCUS process adjustments, while offline methods provide detailed analyses for long-term strategic improvements. These innovative measurement techniques are key to optimizing the capture, utilization, and storage of CO_2, thereby bolstering the safety and efficiency of CCUS operations.

Supporting Regulatory and Operational Excellence: By aiding in the development of key documentary standards, specifications, and regulations, MetCCUS is instrumental in establishing a comprehensive framework for the safe and efficient functioning of CCUS technologies. These efforts guarantee that the CCUS industry operates within a clearly defined regulatory environment, promoting safety, environmental protection, and operational effectiveness. Additionally, MetCCUS's focus on addressing metrological challenges aids the CCUS industry in advancing towards carbon neutrality and playing a significant role in the global effort against climate change.

Iris de Krom's presentation emphasized metrology's crucial role in addressing the measurement challenges associated with CCUS technologies. Through the MetCCUS project's robust metrological framework, the CCUS industry is poised to achieve the accuracy and reliability needed for CO_2 purity and composition analysis. This endeavour is not merely essential for meeting regulatory requirements but pivotal for the safe and effective deployment of CCUS technologies across Europe. The project's success will significantly propel CCUS technology forward, marking a notable advancement towards achieving global carbon neutrality and mitigating climate change's impacts.

Session 3: Learnings from trying to set a proper CO_2 stream specification for the whole CCS value chain by Harald Tlatlik (Wintershall Dea AG), Zero Emissions Platform

Harald Tlatlik provided an insight into the challenges involved in establishing a unified CO_2 stream specification applicable across the entire CCS value chain. Highlighting the inherent impurities found in CO_2 streams, Tlatlik underscored the importance of developing specific standards tailored to each segment of the CCS process, from emission sources, through transportation methods, to final injection or utilization strategies. He discussed the difficulties emitters face, particularly those without waste heat recovery capabilities, which may lead them to prefer lower purity levels for CO_2 due to cost implications. Tlatlik touched on the economic and technical viability for small businesses in purifying CO_2 to the required standards, suggesting that this role might be better managed by specialized partners through a hub concept for CO_2 purification.

A significant obstacle identified in the quest for a standardized approach is the absence of a universal specification governing the CO_2 stream's composition throughout its lifecycle. This lack of a unified framework means that each phase of the CCS value chain; emission, transportation, and injection/utilization, operates under its unique set of requirements and standards. Tlatlik pointed out the urgent need for a Europe-wide CO_2 stream specification to ensure both consistency and safety across the CCS operations, a move that would facilitate smoother transitions between each stage of the CCS chain.

During transportation, Tlatlik noted the crucial importance of maintaining the integrity and reliability of transport assets, especially considering that high purity requirements for pipeline transportation can be a significant factor in reducing capital expenditures but the principal capability of transporting low purity CO2 is strong advantage compared to batch transport (ship, train, truck). He further explained that consistent specifications are crucial to meet the strict purity demands and to handle logistics efficiently, as the balance between demand and supply of CO_2 is not yet well-defined.

The discourse revealed that current standards predominantly focus on individual links within the chain, lacking a holistic view that encompasses the entire process. However, there is a burgeoning effort to bridge this gap, as evidenced by the involvement of the CCUS Forum Expert Group on CO_2 Specifications. This group is dedicated to outlining the critical components necessary for a value chain-wide specification, recognizing the complexity and interconnectivity of the CCS process. Emerging initiatives, including those spearheaded by CEN TC 474 and DVGW C260, are striving to address the entire value chain. These efforts aim to introduce a level of coherence and integration previously unseen in the CCS field, targeting the establishment of comprehensive and universally applicable specifications.

Building on the key takeaways from Harald's insightful presentation, it is crucial to recognize the significant challenges and strategic considerations in developing a unified CO_2 stream specification across the CCS value chain. A critical observation made was the identification of emitters (including processes of purification and compression) as the most substantial cost factor and the least understood link within the CCS value chain.

Finally, the Injection phase was discussed as being crucial for the storage capacity of the injection site, where high purity of the CO_2 stream greatly benefits the operational efficiency and safety. Tlatlik stressed that well-defined and consistent CO_2 streams are vital for the smooth operation of the injection process. However, he also pointed out that site-specific purification at this stage is often not feasible, making it essential to ensure the CO_2 stream meets the required specifications before it arrives.

Tlatlik's presentation made it clear that establishing a comprehensive, value chain-wide CO_2 specification is a complex and ongoing process that necessitates a clear understanding of each segment's unique requirements. The path forward will require a unified effort from all stakeholders to reconcile different interests and establish technical standards that align with environmental objectives and deemed essential for the successful scale-up and enhancement of CCS operations' efficiency

Session 4: Making CO_2 specifications work for the CCS value chain for safe operations by Imran Abdul-Majid, Northern Lights

Imran Abdul-Majid's presentation explored the intricate relationship between the technical requirements and commercial considerations in the CCS industry. He began by paralleling the CCS value chain's emphasis on safety with the familiar adage that one must first secure their own safety before helping others. This analogy served to highlight the essential role that CO_2 specifications play in maintaining the integrity of the transport and injection infrastructure and the importance of emitters adherence to these specifications.

Imran drew attention to recent technical learnings, particularly on NOx and associated cross reactions, which pose a significant risk of corrosion. Further, the industry's initial understanding was that CO_2 streams with low water content were non-corrosive. However, this has been proven incorrect, especially when such streams contain "high" levels of NOx, along with other impurities. This revelation has prompted a reduction in the permissible levels of NOx, and the CCS industry at large is embedding these new learnings.

Another recent insight in the Longship project's CO_2 specifications was the limit for mercury, which was not adequately addressed. Imran reported that mercury's tendency to adsorb into metals and its ability to form a separate phase necessitated a reduction in its allowed levels to the solubility limit. Furthermore, the concentrations of glycols and alcohols, previously unspecified, have now been defined due to their risk of corrosion. A specification regarding particle size has also been instituted, along with parameters for pressure and temperature to mitigate the risk of non-condensable gas supersaturation.

Transitioning to techno-commercial aspects, Imran underscored the impact of CO_2 specifications on the marketability and practicality of CO_2 T&S. Initially, the Longship project's specifications centred solely on impurities pertinent to its existing customers, and inadvertently excluding potential customers dealing with other impurities. Recognizing this gap, the specifications have since been revised to encompass a wider array of impurities, thus inviting participation from additional industry segments. This inclusivity, however, has introduced new commercial challenges. Northern Lights design includes Open Vapor Return system, where customers now face uncertainties regarding the precise composition of the CO_2 they will handle, necessitating greater transparency and accuracy in CO_2 stream reporting.

In conclusion, Imran's presentation highlighted the dynamic nature of CO_2 specification management within the CCS value chain. Safety and integrity form the bedrock of these operations, with an ever-present need to adapt technical specifications considering emerging insights and commercial pressures. By progressively refining CO_2 standards to encompass a broader spectrum of impurities and responding to stakeholder feedback, the CCS industry demonstrates its commitment to fostering both safe operations and market growth. The ongoing challenge lies in balancing these technical updates with the economic demands of a diverse customer base, ensuring that CCS become and remains a viable and effective solution for carbon management.

Session 5: CO_2 specifications in T&S Projects: Pipelines vs shipping by Adekola Lawal, Petrofac

Adekola Lawal's presentation provided an in-depth analysis of the CO_2 specifications for T&S, comparing the pipeline transport with shipping options. Lawal began by setting the context in the CCUS value chain. He continued detailing the different conditions under which CO_2 can be liquefied for transport, outlining three primary scenarios: high pressure at 10°C and 35-45 barg, medium pressure at -30°C and 15-19 barg (adopted by Northern Lights), and low pressure at -50°C, at 6-8 barg (close to the CO_2 triple point). Each of these options presents different technical and economic trade-offs. In general, the ship capacities increase with reducing pressure. Further, leveraging the phase diagram's detailed portrayal of CO_2 states, industry professionals can optimize CO_2 transport by sea, tailoring ship design to specific liquefaction conditions. This not only ensures the stability and safety of the CO_2 cargo but also enhances the economic feasibility of CCUS initiatives by selecting the most suitable phase of CO_2 for long-distance transportation.

Lawal explained that CO_2 specifications for shipping options include higher purity in CO_2 streams compared to pipeline transport. This is due to the requirement of transporting CO_2 in liquid form, which necessitates a low composition of non-condensable gases. Technologies that produce liquid CO_2 generally do not require the oxygen removal units commonly used in pipeline transportation systems.

One of the central points of Lawal's presentation was the impact of impurities on transport design and material integrity. He discussed how:

- The presence of free water can cause extreme corrosion rates, hydrate formation, and ice issues
- Non-condensable gas content is a significant factor in pipeline design,
- The presence of contaminants like triethylene glycol (TEG) can raise the water dew point, further complicating the pipeline transport.

- Lawal also elaborated on specific contaminants such as O_2, SO_x, NO_x, H_2S, and Hg, indicating that these generally increase corrosion risks. Oxygen, for instance, can lead to pitting corrosion, while NO_x and SO_x have the potential to form strong acids that significantly accelerate corrosion, emphasizing the importance of their careful monitoring and control.

Lawal noted that in general, specifications for CO_2 transportation are becoming increasingly strict with project experience. It is particularly important to consider the introduction of new contaminants in the CCUS value chain. Monitoring of amine levels and degradation products is an important example of this.

In summary, Lawal's presentation underscored that mitigating corrosion is a key driver for setting CO_2 transportation specifications. With the introduction of new contaminants from anthropogenic CO_2 sources, the industry must adapt and tighten specifications to ensure safe and efficient CO_2 T&S. As the CCUS industry progresses, the adherence to stringent specifications will be imperative for the successful implementation of both pipelines and shipping methods in the transport of CO_2.

Session 6: Technology review of emerging CO_2 conditioning systems, with a focus on DORA by Juliana Monteiro, TNO

The presentation by Juliana Monteiro provided an insightful analysis on the challenges and solutions associated with removing impurities from CO_2 streams. Monteiro began by framing the problem, posing critical questions: Where do these impurities originate from? How much of each impurity can we expect? And what methods can be employed to separate these impurities effectively?

She highlighted the specific challenge of oxygen removal, especially for plants operating with aqueous amine solvents. The oxidative degradation of solvents leads to significant losses, emits harmful degradation products, and increases corrosion within the plant.

To tackle this issue, Juliana introduced two emerging technologies: nitrogen sparging, currently under development at the University of Texas at Austin, and the Dissolved Oxygen Removal Apparatus (DORA), developed and patented by TNO in the Netherlands. Nitrogen sparging involves injecting nitrogen to strip dissolved oxygen from the CO_2 capture solvents. Conversely, DORA offers a targeted approach, specifically designed to remove dissolved oxygen from the solvent.

Monteiro detailed DORA's development journey. She described DORA as a membrane-based technology designed to remove dissolved O_2 from an amine-based solvent. This technology uniquely prevents other components, like amines and CO_2, from being stripped through the membrane. This occurs before the solvent enters the thermal regeneration step in the stripper column. DORA progressed from TRL 0 to TRL 5 in the ALIGN-CCUS project (2017-2020), achieved TRL 5 in the LAUNCH CCUS project (2019-2022), and its current advancement to TRL 7-8 in the Membrane-assisted Dissolved

Oxygen Removal from amine solution for CO_2 capture (MeDoRA) project (2023-2026). The MeDoRA project aims to demonstrate stable long-term operations at HVC (Alkmaar, Netherlands, Waste-to-Energy, up to 2 years) and RWE (Niederaussem, Germany, power plant, up to 1.5 years), with two different solvents, two different industrial flue gases, and more than 20,000 hours of operation. This project is expected to elevate DORA to a high Technology Readiness Level (TRL 8) and prepare the technology for commercialization by 2026.

Juliana's presentation emphasized the advantages of integrating oxygen removal directly within the CO_2 capture process, particularly through the use of DORA. This approach not only reduces solvent degradation and the emission of degradation products but also decreases the overall corrosion rate within the plant. Compared to nitrogen sparging, Juliana mentions that DORA offers lower capital expenditure (CAPEX) and operational expenditure (OPEX).

Juliana concluded her presentation by addressing the economic and environmental implications of these emerging technologies. Both nitrogen sparging and DORA have demonstrated the capability to separate up to 90% of the oxygen in the solvent, significantly reducing the oxidative degradation of amine solvents. However, the economic impacts of this reduced degradation are not yet fully quantified. Preliminary estimates suggest that the cost of oxygen separation could be in the range of $0.25 per ton of CO_2 for nitrogen sparging or even lower for DORA.

In summary, Juliana Monteiro's presentation provided a comprehensive overview of the challenges and solutions associated with removing impurities from CO_2 streams in carbon capture processes. By highlighting the advantages of emerging technologies, particularly DORA, Monteiro underscores the potential for efficient and cost-effective CO_2 conditioning systems.

Session 7: Technology Review of Emerging and Commercially Available CO_2 Conditioning System Processes, Ray McKaskle, Trimeric

In a comprehensive presentation, Ray McKaskle provided an in-depth review of the current state and future directions of CO_2 conditioning technologies. The focus was on methodologies designed to reduce impurities in CO_2, catering to the stringent specifications required for T&S projects. Ray's analysis covered both established and emerging technologies aimed at purifying biogenic and post-combustion CO_2 from common pollutants such as H_2O, O_2, N_2, H_2, SOx, H_2S, NOx, CO, and hydrocarbons (VOC/HAP). He also addressed technology gaps, specifically the challenge of reducing NOx to < 10 ppmv in post-combustion CO_2, alongside concerns regarding mercury (Hg) and particulate matter (PM).

Ray 's presentation underscores the multifaceted challenges inherent in CO_2 capture and conditioning from flue gas emissions, primarily due to the presence of a broad spectrum of contaminants. These contaminants complicate not only the capture process but also the subsequent CO_2 conditioning, necessitating advanced purification techniques to prepare CO_2 for transport, storage, or utilization. Moreover, Ray adeptly highlights the operational challenges posed by intermittent operations, which can add another layer of complexity to the conditioning process. He also elucidates the escalating difficulty of CO_2 conditioning as a function of fuel type, indicating a spectrum where natural gas presents the least challenges, escalating through coal, refinery fluid catalytic cracking (FCC) flue gas, waste incinerators, and culminating in the emissions from cement and steel production. Despite these challenges, Ray identifies a silver lining in the generally higher CO_2 concentrations found in the flue gases of more contaminant-rich sources, which, in theory, could favour the efficiency of capture technologies. This nuanced perspective Ray provides serves to underline the intricacies of CO_2 capture and conditioning, emphasizing the critical need for tailored solutions that address the specific challenges posed by different emission sources and their contaminant profiles.

In his discussion, Ray emphasized the pertinence of upstream improvements in enhancing the efficiency and feasibility of CO_2 capture and conditioning processes. He elaborated on the importance of improving or incorporating advanced pollution control equipment upstream, which not only streamlines CO_2 capture by removing or reducing contaminants but also yields the ancillary benefit of curbing other pollutant emissions. Ray provided examples of beneficial modifications, such as the adoption of low NOx burners, exhaust gas recirculation, flue gas desulfurization, and the implementation of baghouses or electrostatic precipitators, along with selective and/or non-catalytic reduction systems.

The need for CO_2 dehydration was underscored, with a specific case study of a TEG Dehydration Unit designed for a 21 MMscfd, 400 kTPA CO_2 capture from an ethanol plant presented. Water can freeze in CO_2 processed below 32 °F (0 °C), CO_2 can form a solid hydrate with water at temperature > 32 °F (0 °C), and CO_2 is corrosive when a free liquid water phase is present. In his discussion, Ray informed on how much dehydration is required. Limits are expected to be based on review of processing conditions and CO_2 transport method.

The detrimental effects of oxygen presence in CO_2 streams were explored, including its role in enhancing corrosiveness, promoting biological growth, oxidizing TEG, and glycerol, and reacting with H_2S to form harmful compounds. Ray further delved into emerging options for oxygen removal from CO_2, such as liquefaction and distillation, which is well proven for meeting a 10 ppmv oxygen limit in CO_2 and catalytic reduction, which has been proposed for meeting 10 ppmv limit in recent years in CCUS and DAC but Trimeric was not aware of this being demonstrated in a commercial application.

The management of NOx before and during capture was discussed. Upstream technology does not eliminate all NO_X and can be difficult or costly to retrofit at existing site. Many technologies are being discussed for NO_X removal from CO_2 during CO_2

processing, some may be commercially offered, but it was unclear to Trimeric if any are being successfully applied in the field.

Ray's presentation was a deep dive into the complexities of CO_2 conditioning, offering a holistic view of the current landscape and emerging technologies. By highlighting both the challenges and solutions, Ray shed light on the path forward for the CCUS industry to achieve greater efficiency, safety, and compliance with environmental standards. The insights provided serve as a valuable information for industry professionals seeking to navigate the evolving field of CO_2 conditioning.

Session 8: Economic assessment of CO_2 purification units for CCU by Josephine Vos, Delft University of Technology

Josephine Vos's research aims to fill the knowledge gap by focusing on a case study involving a bioethanol plant as the CO_2 source. The study examines the high-temperature co-electrolysis of CO_2 and steam to produce syngas, assessing the need for and impact of CO_2 purification within this context.

The presentation delved into the economic implications of purifying CO_2 for use in CCU, a subject critical yet underrepresented in current literature. The need for CO_2 in CCU applications introduces a complex landscape of purity requirements distinct from those found in traditional T&S scenarios. Unlike T&S, which may tolerate broader purity ranges, CCU technologies demand specific levels of CO_2 purity, directly influencing the selection of purification technologies and their related costs. This variance underscores the strategic importance of understanding and integrating precise purification processes to meet the nuanced needs of CCU applications, highlighting a significant departure from conventional approaches.

The presence of trace impurities, especially NOx and SO_2, poses significant challenges to the efficiency and effectiveness of CO_2 electrolysers, crucial components in the CCU technology suite. These impurities adversely affect electrolyser performance by reducing selectivity and CO_2 conversion efficiency. Moreover, the presence of sulphur and metallic traces can cause irreversible damage to the catalyst, severely limiting the long-term operational viability of these systems. This detrimental impact underscores the critical need for stringent purification standards to ensure optimal performance and longevity of CCU technologies.

A notable gap in current techno-economic assessments is the lack of consideration for CO_2 purification processes. This oversight creates a knowledge vacuum, potentially underestimating the economic implications of CO_2 purification on the design and operation of future CCU plants. By omitting these considerations, existing assessments fail to capture the full scope of costs and technical challenges associated with meeting the specific purity requirements of CCU technologies. Addressing this gap is crucial for accurately forecasting the techno-economic performance of CCU initiatives, ensuring that future projects are both economically viable and technically feasible.

The economic assessment underscores the importance of incorporating CO_2 purification into the design and economic analysis of CCU technologies. Preliminary findings suggest significant cost implications, potentially altering the overall business case for future CCU projects. Future research will explore advanced purification techniques, such as temperature swing adsorption units, alongside strategies for CO_2 recycling and heat integration, to refine the economic and operational models for CCU plants.

The incorporation of CO_2 purification into the overall assessment of CCU technologies is poised to unveil notable disparities in cost projections. Preliminary estimations indicate that the inclusion of purification processes could lead to orders of magnitude differences in the costs associated with CO_2, compared to scenarios where purification is not considered. This revelation points to a significant oversight in traditional cost analysis, which often overlook the complexities and financial implications of achieving the requisite CO_2 purity for CCU applications. Consequently, a more holistic approach to evaluating CCU technologies becomes imperative, one that fully integrates the economic impact of CO_2 purification.

The pivotal role of CO_2 purification in shaping the techno-economic landscape of future CCU plants cannot be overstated. As research and development efforts continue to evolve, the impact of purification on both the design and economic viability of CCU technologies emerges as a central area of focus. Addressing the challenges and opportunities associated with CO_2 purification is essential for advancing the field, suggesting that this area will be a critical vector for future investigations. By delving deeper into the intricacies of CO_2 purification, researchers and industry stakeholders can unlock new avenues for innovation, enhancing the feasibility and effectiveness of CCU technologies in the quest for sustainable carbon management.

Session 9: Selecting Cost Effective CO_2 Conditioning Technologies by John Woods, Wood

In his enlightening presentation John Woods discussed the technological arsenal available for CO_2 conditioning, showcasing a variety of technologies tailored to specific contaminant removal challenges. These technologies include solid scavenger adsorption for oxygen removal, caustic direct contact coolers for managing NOx and sulphur compounds, catalytic oxidation & adsorption for sulphur and hydrocarbons, and methods like mixed metal sulphides for dealing with contaminants including mercury and heavy metals. The discussion underscored the need for a targeted approach to CO_2 conditioning, where the choice of technology is dictated by the unique composition of the CO_2 stream and the specific requirements of the end-use application.

In a further exploration of cost-effective CO_2 conditioning strategies, John Woods delved into the intricacies of wet gas compression and oxygen removal. He explained that low-pressure (LP) wet CO_2 from the capture process necessitates compression to pressures exceeding 25 barg to facilitate drying. A focal point of his discussion was the catalytic oxidation method for oxygen removal, aiming to reduce oxygen levels to less than 10 ppm mol using hydrogen or methane. As an example, he cited the use of the JM PURAVOC™ catalyst, a platinum-based solution that operates effectively at temperatures above 150°C, leveraging the heat generated from compression. Moreover, he pointed out that hydrogen or methane could be introduced into the feed to catalytically convert oxygen into water or CO_2, respectively. This process exemplifies the nuanced approach needed to select technologies not only for their efficacy in contaminant removal but also for their operational efficiency and cost-effectiveness in the broader scheme of CO_2 conditioning and purification.

In his analysis of technology selection for oxygen removal between cryogenic distillation and oxygen removal, Woods emphasized that cryogenic distillation should be considered when the oxygen concentration in CO_2 feedstock exceeds 300-600 ppm mol. He pointed out that at higher oxygen concentrations, the cost of using a catalytic oxidation reactor escalates significantly due to the need for multiple parallel beds and the substantial volume of platinum-based catalyst required. Additionally, John highlighted the necessity to address the co-removal of other contaminants, such as nitrogen/argon and methane or hydrogen, which could influence the selection of purification technology. This co-removal strategy, particularly with distillation, might dictate the choice of technology due to its efficiency in eliminating multiple contaminants simultaneously, underscoring the importance of a holistic approach in selecting the most cost-effective and efficient purification method.

Mr Woods presentation underscored the imperative need for meticulous removal of impurities in CO_2 streams, particularly when they pose risks of reducing efficiency, damaging equipment, or piping, or creating hazardous environments. He highlighted the stringent current CO_2 specifications for pipeline and liquid transport, prompting a revaluation of the necessity for such tight controls on certain components, most notably NOx. The variability in CO_2 contaminants, largely dependent on the CO_2 source, necessitates a diverse array of purification technologies, with particulate removal, sulphur removal, dehydration, mercury, and oxygen removal technologies being well defined. Techniques such as water wash for the removal of acids, alcohols, amines, and ammonia are also well established. Woods suggested grouping contaminant removal processes as a strategy to reduce the number of separate processing steps, thereby saving costs.

However, gaps remain in our understanding and experience with heavily contaminated CO_2 streams, particularly concerning the use of specialist adsorbents and catalysts, and the removal of BTEX, hydrocarbons, and volatile organic compounds (VOCs). Identifying the components of VOCs present and understanding their removal processes are critical areas needing further exploration. Wood advocates for additional research in membrane separation technologies for contaminant removal from CO_2, understanding hydrate formation temperatures in the presence of impurities, and identifying contaminants that may interfere with or poison catalysts/adsorbents. Addressing these gaps is crucial for advancing CO_2 conditioning technologies, ensuring they are both effective and cost-efficient in facilitating the safe and sustainable use of CO_2 in various applications.

Woods' presentation not only illuminated the intricacies of CO_2 purification but also emphasized the critical role of selecting the right conditioning technologies in enhancing the overall efficiency and cost-effectiveness of CO_2 capture and utilization projects.

Session 10: Workshop synthesis by Dr Owain Tucker, Shell

In concluding the CO_2 conditioning workshop, Owain provided a synthesis of the discussions and presentations, highlighting the dynamic nature of the CCUS landscape. He emphasized the importance of continuous learning and adaptation, as evidenced by projects like Northern Lights, underscoring the need for transformation in response to evolving challenges.

Trimeric emphasized the importance of drawing valuable lessons from the CO_2 Enhanced Oil Recovery (EOR) industry in the United States, highlighting it as a critical learning opportunity for managing CO_2 streams. This perspective was reinforced throughout several dialogue during the workshop.

The discussion led by Josephine Vos, brought to light the stringent nature of dealing with CO_2 contaminants in CCU processes. Owain stressed the necessity of acknowledging these challenges when advocating for CCS technologies to policymakers, ensuring informed decisions that guide the sector's development.

A critical takeaway from the workshop was the realization that specifications for CO_2 transport and storage are not one-size-fits-all but heavily depend on the source's specific impurities. This realization calls for a tailored approach to handling CO_2 streams, especially when dealing with reactive substances like SOx and NOx, which, when combined, could exacerbate corrosion in pipelines. Owain likened SOx and NOx as naughty dance partners. When you bring them together on the dance floor, they cause problems. He mentioned that what we are increasingly discovering interaction between these two substances in pipelines potentially create new problematic agents. The need for further research into NOx was a recurring theme throughout the discussions. O_2 was also noted to be a complicating factor in CO_2 conditioning.

Owain highlighted the pressing need for advanced measurement technologies to accurately detect and quantify impurities, pointing out the necessity of investment and intellectual property development to bring these technologies to maturity.

Discussing conditioning technologies, Tucker underscored the need for solutions that are both effective and practical, advocating for turnkey systems that minimize processing steps and are easily deployable across various contexts.

A particularly poignant moment in Owain's remarks addressed the management of waste streams resulting from CO_2 conditioning. This often-overlooked aspect demands careful consideration, as the decision on how and where to separate impurities significantly influences the entire CCS chain.

In summary, Dr Tucker wrapped up the workshop by reflecting on the wealth of knowledge shared and the path ahead. The collaborative efforts and discussions underscored the complexity of CO_2 conditioning and the collective drive towards innovative, sustainable solutions. His parting words left a strong message of gratitude for the participants' contributions and an optimistic outlook for the continued progress in the CCS domain.

Conclusions

- The development of metrology infrastructure for monitoring CO_2 in industrial processes cannot be overemphasized. This involves creating new traceable facilities, including primary power standards for calibration and systems for quantifying CO_2 leaks from pipelines, ships, and storage locations. The METCCUS project is geared to produce the necessary primary standards, sampling methods, analytical techniques, and models to support the industry in specifying operational conditions and performing the required measurements in CO_2 capture, transport, and storage.
- The challenges of establishing a unified CO_2 stream specification across the entire CCS value chain reveal the complexity of harmonizing standards amidst inherent impurities and varied requirements from emission to injection. A significant issue is the absence of a universal specification, highlighting the need for a Europe-wide standard to ensure consistency and safety across CCS operations.
- The evolving nature of CO_2 specifications within the CCS value chain underscores the critical balance between technical requirements and commercial considerations for ensuring safe operations. Recent technical findings, such as the corrosive potential of CO_2 streams with high levels of NOx and the need to limit mercury levels, reflect the industry's evolving understanding and the necessity to continuously update CO_2 specifications. These updates are not just technical corrections but responses to the complex interplay of safety, integrity, and marketability within the CCS framework.
- Shipping options, which typically demand higher CO_2 purity due to the necessity of transporting CO_2 in liquid form, present unique challenges compared to pipeline transport. This includes the significant impact of impurities on transport design,

material integrity, and the heightened corrosion risks associated with certain contaminants. The evolving understanding of these risks, especially with new contaminants from anthropogenic CO_2 sources, necessitates stricter CO_2 transportation specifications to mitigate corrosion and ensure safe, efficient transport.

- The introduction of technologies such as nitrogen sparging and the Dissolved Oxygen Removal Apparatus (DORA) presents innovative approaches to remove dissolved oxygen from capture solvents, each offering distinct advantages in terms of operational and economic efficiency. DORA, with its targeted removal process and the potential for lower capital and operational expenditures, demonstrates a promising advancement towards integrating oxygen removal directly within the CO_2 capture process.
- Intermittent operations may add a layer of complexity to the conditioning process due to the variability in CO_2 composition and flow rates stemming from fluctuating industrial activity. Such fluctuations may introduce operational inefficiencies and complicate the management of the conditioning process. This variability may necessitate a highly adaptable conditioning process, and flexible operational protocols, to ensure the CO_2 consistently meets quality standards despite changing inputs. Further, these challenges may have an economic impact, as adapting to the intermittent nature of operations can lead to higher capital and operational costs.
- The importance of upstream improvements and advanced pollution control equipment in enhancing the efficiency and feasibility of CO_2 capture and conditioning processes was highlighted. Furthermore, it emphasizes the need for dehydration to prevent issues like freezing and corrosion, alongside exploring emerging conditioning options.
- An often-overlooked aspects of conditioning and CO_2 stream specification for CCU technologies was highlighted. It sheds light on the unique purity requirements for CCU applications, which significantly differ from those for traditional T&S and examines how these requirements influence the selection and cost of purification technologies. The study reveals that trace impurities, especially NOx and SO_2, adversely affect the efficiency and longevity of CO_2 electrolysers, a crucial component for CCU technologies, thereby emphasizing the need for stringent purification standards.
- Despite advances in CO_2 conditioning technologies, significant gaps persist in our comprehension and practical experience with handling heavily contaminated CO_2 streams. These gaps are particularly pronounced in the application of specialist adsorbents and catalysts tailored for the removal of BTEX (Benzene, Toluene, Ethylbenzene, and Xylenes), hydrocarbons, and VOCs. The intricacies of identifying the specific components of VOCs present in these streams and fully understanding the mechanisms and efficiencies of their removal processes underscore critical areas for further investigation.

- The discussions illuminated the evolving challenges faced in conditioning CO_2 from power and industrial sources, highlighting two distinct strategies: conditioning at the source to address smaller volumes of CO_2 or establishing a gathering network for conditioning at larger volumes. Each strategy is characterised with its own economic and operational implications. This reveals a pivotal decision-making juncture for the industry in determining the most effective locations and methods for CO_2 conditioning, fundamentally impacting the operational, safety, and economic outlook of CCS infrastructure.
- The discussion on conditioning technologies advocated for practical, effective solutions, emphasizing turnkey systems that streamline processing steps and facilitate deployment across different contexts. Further, and importantly, the management of waste streams from CO_2 conditioning was identified as a critical, yet often overlooked, consideration, significantly influencing the CCS value chain.

Recommendations

Following the discussions at the IEAGHG workshop on the comparative techno-economic assessment of CO_2 conditioning technologies, the expertise, and experiences shared warrant the framing of a technical specification for a full-fledged IEAGHG study. This proposed study aims to bridge the knowledge gaps identified during the workshop. It will address, among other issues, the complex interplay of technical, economic, and operational considerations from the purity requirements for CCUS technologies to the economic implications of conditioning heavily contaminated CO_2 streams. The study seeks not only to enhance our understanding and application of CO_2 conditioning technologies but also to inform strategic decisions and policy formulations that will ultimately shape the future landscape of CCUS.

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