U.S. Department of Energy, Office of Fossil Energy and Carbon Management – U.S.-Norway Bilateral Meeting

Prepared for:

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U.S.-Norway Bilateral Meeting

Executive Summary

On October 31, 2023, the Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) with support from the United States Energy Association (USEA), led a hybrid (in-person and virtual) workshop of experts to discuss carbon capture and storage (CCS) policies implemented across both the United States of America and Norway, as well as areas for continued and new collaboration between research organizations and industry in the two countries.

The meeting, held at the USEA office in the Ronald Reagan International Trade Center in Washington D.C, consisted of continuous presentations on CCS progress updates given by and to industry, research organizations and government representatives of both countries. The workshop was generally split into topics arranged chronologically as carbon storage, carbon transport and infrastructure, carbon dioxide removal (CDR), point-source carbon capture, and hydrogen energy production. Each topical section concluded with an open discussion between all members of the workshop regarding cooperation between the U.S. and Norway.

Presentations regarding CCS status in the United States focused largely on the funding provided by the DOE through the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) for nationwide carbon capture, sequestration, and hydrogen projects. Presentations with a focus on the status of CCS projects in Norway covered the CLIMIT program, heavily emphasized the Northern Lights project, and discussed the on-going carbon capture facility construction.

During periods of open discussion, a common question was relating to how the United States and Norway can cooperate in the development of CCS policies and technologies. The consensus among many of the attendees is that government regulatory uncertainty increases the difficulty of commercializing technology. A significant portion of the discussion time was dedicated to postulating the foundation of a knowledge and data-sharing platform and/or consortium.

Agenda

The agenda for the workshop is in Table 1.

Table 1. Workshop Agenda

Time	Topic	Speaker/Affiliation
8:30	***The Larger Picture***	
8:30	Welcome from USEA Hosts	Mark Menezes, United States Energy Association (moved to Day2, Michael Moore gave a short welcome)
8:35	Opening and U.S. Carbon Management Overview	Brad Crabtree, U.S. DOE
8:50	Norway Carbon Management Status and Overview	William Christensen, Norwegian Ministry of Energy
9:05	U.S. Updates on Carbon Management Awards, BIL and IRA	Noah Deich, U.S. DOE
9:20	Norwegian Activities, Brief Updates on Projects	**Status of Northern Lights:** Børre Jacobsen **Industrial CCS Clusters: Recent development capture technology** Jørild Svalestuen, Gassnova (online) **New storage R&D projects:** Kari-Lise Rørvik, Gassnova
10:00	***Break***	
10:15	Storage	Overview of Activities, moderated by Kari-Lise Rørvik **Report from the 6th International Conference on Offshore Geologic Storage** Katherine Romanak, University of Texas - Bureau of Economic Geology (UT-BEG) **ACT Projects with U.S. and Norway Participation** *Ensure (ACT3):* Volker Oye, Norsar (online) *SPARSE (ACT4):* David Alumbaugh, LBNL *PERBAS (ACT4):* Stanislav Glubokovskikh, LBNL **CO_2 DataShare** Darin Damiani, DOE-FECM; Grethe Tangen, SINTEF (online)
11:15	Discussion – Industry Needs – What can we learn from offshore experience?	Moderated by Darin Damiani **U.S. Panelists** Alex Bump, UT-BEG, GoMCarb George Koperna, ARI, SECARB-Offshore Ross Markwort, ExxonMobil Chris Walker (online) and Marcus Koblitz, BP Peng Yi and Phil Ringrose (online), Equinor **Norwegian Participants** Sara Gasda, Norce (online) Volker Oye, Norsar (online) Philip Ringrose, Equinor Research Centre (online)
12:15	Discussion: Areas of Cooperation in Storage	Facilitated by Darin Damiani and Kari-Lise Rørvik
12:30	***Lunch***	
13:30	Transport and Infrastructure	Transport Program Overview and Priorities (both sides): Bob Smith and Kari-Lise Rørvik
13:50	Topics of Common Interest	**Pipeline Impurities and Specifications**

Time	Topic	Speaker/Affiliation
		Arne Dugstad, Institute for Energy Technology (online) **Carbon Transport Research Consortium** Bob Smith, U.S. DOE **Repurposing Infrastructure** Bob Smith, U.S. DOE **Public Engagement** Aslak Hellestø, Northern Lights (online) **Discussion: Panel members from industry and research**
14:30	Discussion: Areas of Cooperation in Transport and Infrastructure	Facilitators: Bob Smith and Lars Ingolf Eide
14:45	***Break***	
15:00	CDR	Session chair and discussion moderator: Rory Jacobson, U.S. DOE
15:00	CDR Overview, Program Activities and Updates	
15:00	Mission Innovation CDR Status	Mark Ackiewicz, U.S. DOE
15:10	Snapshots on CDR in the US and Norway	U.S.: Rory Jacobson, U.S. DOE Norway: Lars Ingolf Eide and Jørild Svalestuen, Gassnova SF
15:30	Business Models – Examples from Industry	U.S.: Andrew Fishbein, Climeworks (online) Norway: Jon C. Knudsen, Aker Carbon Capture
16:00	Discussion: Areas of Cooperation in CDR	Facilitated by Rory Jacobson and Lars Ingolf Eide
16:15	***Adjourn Day 1***	
	DAY 2	
8:00	Point Source Capture	Session chairs and discussion moderators: Åse Slagtern, Research Council of Norway, and Dan Hancu, U.S. DOE
8:00	Introduction and Program Updaters	Åse Slagtern and Ron Munson
8:30	Technology Scale-up and Commercialization Pathways	Moderated by Åse Slagtern **North American companies** Eric Meuleman, ION Claude Letourneau, Svante **Norwegian companies** Jon C. Knudsen, Aker Carbon Capture Torleif Madsen, Compact Carbon Capture, Baker Hughes
9:20	Test Centers' Roles in Technology Development	Moderated by Ron Munson **MRV Discussion** Karl Anders Hoff, Tiller John Northington, National Carbon Capture Center Ismail Shah, TCM Kunlei Liu, University of Kentucky ACT Projects: SCOPE Karl Anders Hoff **Discussion: Areas of cooperation in Point Source Capture** Facilitated by Åse Slagtern and Dan Hancu
10:30	***Break***	
10:45	Hydrogen	Session chairs and discussion moderators: Bob Schrecengost, U.S. DOE and Åse Slagtern
10:45	National Activities U.S.	Eric Miller and Bob Schrecengost
11:05	National Activities Norway	Overview: Åse Slagtern, RCN

Time	Topic	Speaker/Affiliation
		Fionn Iversen, HyValue Steinar Eikaas, Equinor hydrogen strategy
11:45	Hydrogen Related Issues for Discussion	**Safety Aspects** Nick Barilo, PNNL **LCA/Carbon footprint**Greg Cooney, U.S. DOE, and Pradeep Vyawahare,
12:30	Discussion: Areas of Cooperation in Hydrogen	Facilitated by Åse Slagtern and Bob Schrecengost
12:45	Meeting Wrap-up	Åse Slagtern, Kari-Lise Rørvik , and Mark Ackiewicz
13:00	**Meeting Adjourns**	

Notes from the Workshop

DAY 1

The Larger Picture

Welcome from USEA Hosts and U.S. Carbon Management Overview

Brad Crabtree kicked off the meeting by discussing the importance of US-Norway relations in security, energy, and climate change mitigation. This partnership in carbon management goes back about 20 years, and is likely the most important bilateral relationship of its kind in the world. The Department of Energy (DOE) – Office of Fossil Energy and Carbon Management takes this relationship very seriously. War in recent years has emphasized the crucial role natural gas plays in world economics, and the DOE admires Norway's continued climate awareness and regulations regarding methane emissions and clean gas.

In the United States, the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) have set policies to incentivize national participation in the Biden Administration's net-zero carbon goals. $189 million has been allocated to carbon capture and storage (CCS) field studies, $820 million for 10 CCS pilot plants, $2.25 billion for carbon storage at 20 to 40 commercial sites and regional direct air capture (DAC) hubs, and $1.2 billion for seven announced hydrogen hubs. Crabtree notes that the U.S. needs to upscale permitting—no easy task. Additionally, work is required to persuade the public, especially stakeholders, to accept CCS technology. The Biden administration has emphasized community engagement to mitigate further inequities, especially in regions with long-standing pollution inequities. Norway has proved exceptional with regard to public acceptance of CCS development and best practices in technology buildout.

Norway Carbon Management Status and Overview

William Christensen presented on recent developments of CCS in Norway, beginning with a personal work history within the United States as a counselor for energy at the Norwegian embassy, and noted the appreciated cooperation between the United States and Norway. Christensen noted the difficulties Norway experienced regarding CCS between 2000 and 2020, but that the CLIMIT program allowed the country to continue CCS development. The Longship Project, a carbon dioxide (CO_2) transport project by ship from several on-land CO_2 capture sites via an onshore terminal to offshore storage, was remarked as the most recent important government-supported project. Six new licenses for offshore CO_2 storage have been awarded between 2022 and 2023. There are ambitions for hydrogen pipelines between Germany and Norway.

The objectives of the Norwegian government are to demonstrate that CCS is a part of the climate change solution, speed up global development, develop new green industry in Norway, facilitate development of CO_2 on a commercial scale, and develop permanent and safe carbon storage solutions. Moving forward Norway officials have articulated a need for further public/political support, countries to invest in CCS to reach economies of scale and bring down costs, predictability in regulatory frameworks, and more countries to ratify the amendment to the London Protocol to allow for export of CO_2 for sub-seabed geologic storage.

U.S. Updates on Carbon Management Awards, BIL and IRA

Noah Deich presented the new tax credits from the IRA and new permits awarded by the DOE. The state of CCS in the United States is purely driven by incentives, yet investment communities are historically hesitant to commit to CCS projects, with the exception of a

small, niche group of emitters. Generally, there is even greater hesitation to invest in low CO_2 concentration projects until proof-of-concept has been performed by the DOE on high concentration projects. As an overview of major U.S. federal investments, the BIL allotted $12 billion to carbon management, and $7 billion to hydrogen hubs. The IRA incentivizes companies by providing up to $85/ton for industry and electric power carbon storage, $60/ton for enhanced oil recovery (EOR) carbon storage and utilization, and $180/ton for DAC carbon storage.

Many industries are breaking even on costs versus tax credits, which encourages optimism for the near future of storage costs. Generally, high purity CO_2 is most profitable, while low purity CO_2 is not profitable. Although heavily subsidized by the DOE, investors across industries are becoming more interested in DAC over time, but capital investment remains challenging. The recently announced Carbon Dioxide Infrastructure Finance and Innovation Act (CIFIA) program provides loans that organizations may be able to leverage for CCS investment.

Norwegian Activities: Brief Updates on Projects

Status of Northern Lights

Børre Jacobsen presented a summary of the Northern Lights (NL) project in Norway. Northern Lights is the first open-source CO_2 storage facility that aims to handle an initial 1.5 MMT/year (3%) of Norwegian emissions. Liquid CO_2 is transported by ship to an intermediate onshore storage receiving terminal with a pipeline transport to permanent storage offshore into a continental-shelf saline aquifer. The first phase of Northern Lights is 80% state-funded through the Longship Project (2020), which also includes CO_2 capture at a cement plant and a waste-to-energy facility. NL nnshore facilities are more than 90% complete and will be ready for operation by 2024. Drilling of a two injection wells is complete—confirming in 2020 that the Johansen Formation is suitable for storage—and storage testing with water will begin very soon.

The construction of two of the world's largest liquid CO_2 transportation ships is 60% complete in China, with a third expected by 2025.

Yara, a fertilizer plant in the Netherlands, is expected to capture 800 thousand tons of CO_2 annually. Orsted, a bioenergy plant in Denmark, is expected to contribute negative emissions with 430,000 tons captured annually.

Industrial CCS Clusters: Recent Development Capture Technology

Jørild Svalestuen discussed some of Norway's areas (cluster) of industry. Testing of capture at different clusters requires different test parameters. Testing in silicon and lime industry in CO_2 Hub North has yielded first results of capture rates of 90 to 95%, good stability in the capture process, and emissions measurements showing promising results. In the Returkraft cluster, a waste-to-energy facility, testing on PRISM membrane technology for CO_2 capture will be occurring from May 2023 to May 2024 with the goals of >50% capture rate of fossil-based share of waste, a future capture rate of 90%, and successful evaluation of membrane lifetime in exposure to gas components. After 6 months of testing, results show a capture rate of more than 55%, good CO_2 permeance, and no emissions associated with membrane. The next step is to successfully measure a capture rate of 90%.

New Storage R&D Projects

Kari-Lise Rørvik began presenting by noting the 25-year history of Norway experience with CO_2 storage, and reviewed a timeline of that included Gassnova CLIMIT, TCM, and Longship. Research and development (R&D) relating to CO_2 wells includes SNOWPACCS, REX-CO_2 (reusing existing wells for storage),and automating evaluation of well barriers. R&D relating to monitoring includes accelerating Controlled-Source Electromagnetic (CSEM) technology for efficient and quantitative CO_2 monitoring, DIGIMON: digital monitoring of CO_2

storage projects, and SafeGuard: new technology for long-term monitoring and risk mitigation of CO_2 storage projects.

Storage

Overview of Activities

Report from the 6th International Conference on Offshore Geologic Storge

Katherine Romanak spoke on the topics presented at the 6th International Conference on Offshore Geologic Storage. The global offshore continental shelves represent the largest long-term storage option for gigaton-scale CCS. The inception of the conference was aided by a 2015 carbon sequestration leadership forum (CSLF) Report which asked for international workshops for international knowledge sharing. In the first of these meetings, Philip Ringrose announced the concept that would become the Northern Lights Hub, which has been leading the way as a hub model and ship transportation model. The sixth and most recent conference had 35 countries interested. The technical outcomes of the workshop were reviewed, stating there was lots of project encouragement; measuring, monitoring, and verification plans maturation; and precedence setting for regulations and permits.

The primary area of concern shared among attendees of the 6th International Conference is that an organized response to stakeholder questions is vital to the success of CCS. Recommendations were presented revolving around the dispersion of information to stakeholders and community outreach programs. The overall summary of the conference is that the CSLF taskforce is a large success, with the United States and Norway being the only countries to host the conference.

ACT Projects with U.S. and Norway Participation

Ensure (ACT3)

Volker Oye presented microseismic monitoring of storage sites and that seal integrity verification has become more robust, cost-effective, and publicly available. The Ensure project highlights include Northern Lights, but Canadian datasets that contain many microseismic events was also a focus. The goal is to optimize a microseismic monitoring strategy as it relates to both surface and borehole geophones by matching events seen on high quality data in lower quality data. While distributed acoustic sensors (DAS) is high quality, it is also quite costly—so costly, in fact, that that offshore downhole geophones are not feasible.

Borehole seismic methods have high signal-to-noise ratio while surface nodes have low signal-to-noise, attenuation, and require advanced pre-processing and filter techniques. DAS is a viable source of high-quality monitoring data that is able to identify up to 50% of microseismic events. Surface nodes improve azimuthal coverage, while there are large uncertainties in event location for borehole seismic.

The Ensure project has conducted one of the most comprehensive research efforts to date in order to help understand public views of CCS. Public perception of monitoring is largely unknown because people do not know what CCS is. About 50% of the population surveyed in Canada and Germany have never heard of CCS. Despite the lack of public knowledge, the Ensure project has had a great impact, especially on other projects like Quest.

SPARSE (ACT4)

David Alumbaugh gave a presentation prepared by both he and Amir Ghaderi. SPARSE is a new project. The key targets of the project are to establish a principal node design, quantify key parameters, determine technical requirements for implementation of sparse nodes, and assess performance of sparse monitoring at CaMI.FRS test site, thus driving down costs of surveys by reducing the need for large-scale four-dimensional (4D) seismic surveys. The

project involves a multiphysics approach that implements seismic, gravity, and magnetic data to monitor CO_2 plume activity. The expected outcomes are a geophysical toolbox for SPARSE multiphysics monitoring, conformance tool box, recommendations for technical design, and workflow for designing optimum sparse monitoring systems.

PERBAS (ACT4)

Stanislav Glubokovskikh presented PERBAS, a project dedicated to permanent sequestration of gigatons of CO_2 in continental margin basalt deposits. Basalt reservoirs are difficult to store into, largely due to lack of pore space and permeability. Lava flows (flood basalts), however, allow for permanent storage due to CO_2 reacting with calcium, magnesium, and iron in the rocks and transitioning into carbonates within a few years as opposed to thousands of years in standard storage for carbonate formation.

The first test of injecting CO_2 into flood basalts occurred in the Icelandic Geothermal Zone. Once CO_2 was dissolved in water, it turned into carbonate rock far from the injection zone, avoiding fluid pathways and injection pathways blockage. The Wallula project (a DOE-funded project) experimented with injecting supercritical CO_2 into basalts and found that pores were clogged in very close proximity to the borehole. PERBAS can aid the design of injection sites by developing characterization tools, including imaging of whether the pathways are being mineralized or not, by using materials from the Norwegian continental margin basalt and from India. Reservoir simulations, created at the Colorado School of Mines, will be used to model geomechanical flow. Glubokoskikh wrapped up the presentation with a mention of new geophysical instruments that will be implemented to analyze subsea basalts, coupled with machine learning.

CO_2 DataShare

Darin Damiani, supplemented online by Grethe Tangen, discussed the need to share CCS-related data globally. CO_2 DataShare has the objective to create a comprehensive, user-friendly database that contains seismic data and a few select formation data. For stakeholders, CO_2 DataShare can add value by offering easy discoverability and access to quality data, and cost-reduction of sharing and tracking statistics. Currently, the application consists of datasets from the Johnsen Formation in Norway, three-dimensional (3D) seismic and microseismic from the US (Illinois Basin), and Northern Lights geomechanical data. The application has already seen over 37,000 downloads. The next steps are to enhance data-sharing capabilities, expand scope of portal to cover the whole CCS value chain, establish network activities, clarify relationships with European Open Science Cloud, and similar data-sharing solutions. Additionally, contributions of new datasets are necessary to expand the application. Currently, the overarching issue is that running a database is costly, and CO_2 DataShare does not have a sound method of funding to run the servers.

Two questions were asked by the attendees of the workshop that were unable to be answered concretely: Is there a formalized data taxonomy for the lifecycle of the data, as the establishment of a fundamental taxonomy could be very useful? Has a subscriber-type arrangement been considered? The latter was responded to with the suggestion that the goal is to provide free CCS data.

Discussion – Industry Needs – What Can We Learn from Offshore Experience?

Philip Ringrose began by discussing Equinor Research Centre's projects. Philip shared a pathway to accelerate CCS in the US which aims to store 15 to 30 Mtpa by 2035. The majority of projects will begin after 2026. Technology developments are underway for legacy wells, induced seismicity, impacts of CO_2 leakage, and far field monitoring (offshore CO_2 pressure front). The Horda Platform Region seismic monitoring network (HNET) project does

not have a U.S. stakeholder, but it attempts to listen to microseismic events in offshore environments.

Alex Bump discussed the U.S. CCS landscape for offshore. The Ohio River Valley and Gulf Coast are the two largest sources of CO_2 emissions according to the EPA FLIGHT database. Texas and Louisiana lead the nation in point-source CO_2 emissions. Along the Gulf Coast, legacy wells are abundant, with 1.1 million in the Texas-Louisiana area. There are currently 30 publicly announced storage projects equating to more than five gigatons of storage development. Federal waters, instead of state waters, will soon open to CCS and consist of fewer legacy wells. No projects have been announced that repurpose old wells as of yet.

George Koperna presented on reusing wells for CCS purposes. Reusing legacy wells is expensive, with regulatory uncertainties that inhibit investments, and monitoring is not well understood. Technology is improving to monitor legacy wells with recent developments in offshore environments. EOR shows promise as a mechanism for carbon storage.

Chris Walker reviewed the support of government in mitigation of delays with CCS projects. The Biden Administration has announced CCS projects that includes ARCH2 hydrogen hub and CarbonSafe of the Gulf Coast. BP has been selected for CCS development in Texas and is currently in negotiations. Walker reiterated that regulatory agencies like BOEM and BSEE need to release clear regulations for the benefit of the United States as a nation.

Ross Markwort with ExxonMobil briefly discussed the commitments of ExxonMobil toward CCS in the near future. Markwort reiterated the need for regulatory clarity, to which the BOEM representative responded that there are on-going interagency conversations regarding the official rule. Discussion followed these presentations, with a high focus on uncertainty in the regulatory environment, that included the issue Norway may face where multiple operators are injecting into a single operator and determining fault for events. There was also discussion about the need for further research such as existing legacy and orphaned wells, and how it may affect storage activities, and studies on potential environmental impacts on flora and fauna for offshore injection.

Transport and Infrastructure

Transport Program Overview and Priorities

In Norway, the Longship Project is a first-of-a-kind, open-source transportation structure, CCS project that has demonstrated a full-scale CCS chain. LINCCS links large-scale, cost-effective, permanent CO_2 storage across the CCS value chain and aims to repurpose existing offshore installations, competencies, and technologies. Wintershall Dea and Equinor have partnered up for large-scale CCS value chain development in the North Sea, and will provide an estimated pipeline capacity of 10 to 40 million tonnes by 2037. CO2LOS is a project that covers logistics for volume and cost-effectiveness for risk reduction transportation networks and hubs from various source. Because impurities can create a corrosive environment, the CO2LOS project examines how impurities create corrosion.

In the United States, transport must expand rapidly, through intermodal transport hubs. Bob Smith showed a graphic of a timeline for transport modules. New CO_2 transport front-end engineering and design (FEED) studies and a loan/grant program have been announced. Smith overviewed the national transport FEED awards: the first to Carbon Solutions LLC in Wyoming, and the second to Howard Energy Partners in Texas and Louisianna. Currently, feasibility studies are funded. Smith reviewed the currently user-friendly models and tools for CCS like SIMCCS, Carbon Matchmaker, and TEA/LCA models. Smith reiterated the need for a consortium with inter-agency collaboration on CO_2 transport to regularly discuss research, development, and demonstration of transport mechanisms.

Topics of Common Interest

Arne Dugstad presented on pipeline impurities and specifications. The Institute for Energy Technology has a long history with CO_2 transport, and Dugstad reviewed lessons learned regarding logistics and risks of CO_2 transportation that include corrosion and water-interaction studies. Dugstad discussed new implementations into pipelines like carbon steel for clean and dry CO_2, corrosion-resistant alloys for "wet" CO_2, and project-specific CO_2 specifications to mitigate corrosion from CO_2 capturing-introduced impurities. A large emphasis was placed on how to define acceptable CO_2 stream chemistry.

Bob Smith presented the idea of a carbon transport research consortium to produce guidelines for the management of impurities. Anyone can have the opportunity to join the proposed consortium and aid in constructing a framework that prevents duplication of, and peer-reviews, research. If done correctly, this process should allow for work sharing at reduced cost, increased research credibility, improved chances of achieving project-specific goals, and growing an international knowledge network. The overarching goal is to run with the motto "leave no knowledge behind".

Bob Smith also discussed repurposing infrastructure. Smith noted a number of considerations that include: pressure capacity limitation, route length, prior integrity management history, CO_2 purity level, and possible component swapping. PHMSA (Pipeline and Hazardous Materials Safety Administration*)* has an update for CO_2 pipeline safety regulations that consists of inspections and the repurposing process, environmental impact statements, and harmonization of federal and state laws.
Aslak Hellestø presented public engagement as it relates to the Northern Lights project. The framework for public perception of CCS in Norway is generally psitive. The state benefits from the project through openly-shared knowledge and leveraging the power of advocacy. Hellestø pointed to the Northern Lights visitor center, which has seen over 6,000 annual visitors from 48 countries. Recently, the Northern Lights Summit was held to boast six years of gathering high-level, competent pioneers, policy-makers, and industry visionaries. The Northern Lights webpage has a lot of public information that includes various data and reports for any to access. In general, the local community is strongly supportive of the Northern Lights project, indicating successful public engagement policy.

Discussion – Areas of Cooperation in Transport and Infrastructure

Why is there a spec for maximum allowed nitrogen in CO_2 streams?

4% is generally the maximum allowed nitrogen concentration because nitrogen has a large impact on phases and pressures needed to operate.

A table was displayed that shows specifications getting increasingly low over time with respect to some allowable impurities. What drives this?

Experiments that mix impurities have shown formation of sulfuric acid. Also, if SO_x and NO_x are taken out of the stream, water levels can then be much higher.

Do we tighten specifications around capture, or should we work to find more corrosive-resistant alloys?

It is unlikely that alloy research and development will prevent much corrosion. Transport and storage specifications will push costs of reducing impurities to capture, and the specifications need to be made available.

Has there been any opposition to Norwegian projects? Have communities such as fishermen complained?

Luckily, there has been no major opposition. The rural communities are accustomed to the existing petroleum infrastructure. However, while the communities of Norway are accepting of CCS development now, it's important to remember that it hasn't always been that way. One specific project had to change amine selection in its process due to fears of release of carcinogenic emissions affecting neighboring towns.

Carbon Dioxide Removal (CDR)

CDR Overview, Program Activities, and Updates

Mission Innovation CDR Status

Mark Ackiewicz gave an overview of the CDR mission that includes: acceleration of research, development, and demonstration of technological CDR approaches including DAC, enhanced mineralization, and biomass carbon removal and storage. Additionally, Ackiewicz emphasized long-term secure CO_2 storage and conversion into products. With many countries in the CDR coalition, the highlights have been an established roadmap and action plan, CDR "launch pad" launched in September 2022, which plans to capture at least 1,000 tons CO_2 per year and contribute $100 million to the collective goal by 2025.

Snapshots on CDR in the US and Norway

Rory Jacobson discussed the progress of the DOE with regard to the CDR program. The DOE aims to push scalable and durable capture and storage costs of under $100 per metric ton within one decade. Performance metrics of the Carbon Negative Shot program include less than $100 per net metric ton of CO_2; robust accounting for full life cycle emissions; high-quality and durable storage, with affordable costs demonstrated for measuring, reporting, and verification (MRV) for at least 100 years; and gigaton-scale removal encouragement. Regional DAC hub funding has recently been announced from FEED studies that have shown eventual sequestration of up to one million tons per year. Carbon Negative Shot will continue to fund DAC pilots and offer direct federal government CDR assistance.

Lars Ingolf Eide, on behalf ofJørild Svalestuen, presented Norway's interests in CDR. The longship demo project, cn be consieredas partly a Biomass Carbon Removal and Storage (BiCRS) project, due to the inclusion of biogenic CO_2 from waste-to-energy CCS and the Heidelberg cement plant. Additionally, there is an agreement to receive biogenic CO_2 from a BECCS facility in Denmark. Industries in Norway have a significant potential for CDR implementation while processing biomass with CCS. SINTEF's Global climate fund is investing in R&D for CDR. Norway, through Gassnova, co-leads for BiCRS technical track in Japan and maps potential for additional biomass harvest and demo projects. Norwegian CDR research and development is currently seeking collaboration with other initiatives; international carbon capture, utilization, and storage (CCUS) organizations; and stakeholders.

Business Models – Examples from Industry

Andrew Fishbein presented Climeworks progress with DAC and storage. The DAC projects at Climeworks are meant to address historical and hard-to-abate emissions. The technology implemented is based on a solid sorbent adsorption process. Climeworks journey to impact at scale was reviewed through a projected timeline from company inception to 2050. In 2021, the first commercial DAC plant was commissioned. The Orca plant is the first geothermal-powered DAC and storage facility capable of capturing 4,000 tons per year and permanently storing through mineralization. The Mammoth plant, alsoin Iceland, can capture and store up to 36,000 tons of CO_2 per year with injection boreholes currently underway. While Climeworks has many global projects, the focus is on Norway to scale-up DAC+S. The business model is CO_2 removal to cut emissions, and they rely on a voluntary market

because CDR is not fully integrated into the tax credit incentive market. Climeworks believes upscaling to a gigaton scale is necessary to reach net-zero and a $100 to 300 per ton CDR price.

Jon C. Knudsen discussed business models for CDR as seen from Aker Carbon Capture. Aker Carbon Capture (ACC) is a pure play carbon capture company delivering seven full-scale carbon capture plants totaling 1 million metric tons per year. The Heidelberg Materials cement plant in Norway and Twence waste-to-energy facility in the Netherlands are two clients of Aker Carbon Capture. The Orsted Kalungborg BECCS project in Denmark, another client of ACC, has allowed Microsoft to purchase 2.72 million CDR credits and set a new standard for high-integrity CDR credits. This is the largest CDR offtake agreement in the world to date. A state subsidy can help the economics of the project, but sales of credits can make up gaps necessary to make them profitable. There are some conditions that are crucial for the enablement of bioenergy with carbon capture and storage (BECCS) program: allow support schemes to work in tandem with sale of CDR credits, enable CDR regulation and credit generation for mixed CO_2 streams, carbon removals need to have a high level of integrity, project developers and investors need certainties in planning phase from a regulatory perspective, climate targets should identify role of carbon removal, and alignment with international standards for carbon removal.

Discussion – Areas of Cooperation in CDR

Are there obvious themes or lessons in collaboration we can share with each other?

Monitoring Reporting and Validation and Life Cycle Analysis points to the necessity of standards and the necessity of keeping an eye on the standards for global implications. At the National Energy Technology Laboratory (NETL), there is a test facility where collaborators are welcome to apply to test DAC technology. Knowledge-sharing as business develops is crucial. Another participant commented that boundaries for “sustainable harvesting” for biomass are difficult to describe on a global scale and should be defined in a globally-standard way.

Further discussion focused on financial tools to enable a more robust carbon market. It may be ideal for a banking system to create financial contracts which can be applied to CDR . Many consultants were hired by Microsoft to audit the Aker Carbon Capture plans so that Microsoft could understand the CCS process prior to credits purchasing. While companies should certainly verify process integrity, a thorough and standard contract framework that describes agreed-upon best practices relating to CCS projects may allow companies to feel safer with their investments.

How will DAC be added and integrated into existing pipeline infrastructure?

DAC will scale in parallel with other CDR projects. DAC will need to be proximate to storage or there is no business case. Construction of wide-spread DAC facilities may eliminate the need for lengthy transportation.

End Day 1

DAY 2

Point Source Capture

Introduction and Program Updates

Åse Slagtern presented Climit’s Research & Development & Demonstration (R&D&D) program in Norway. The primary targets of Climit involve decarbonization of industry and

energy resources, large scale CO_2 storage offshore, and developing innovative technology. 148 million kr (about 13.2 million USD) has been split between The Research Council of Norway and Gassnova in 2023. 56% of demo projects and and 44 % of the R&D projects have been R&D of capture. Slagtern reviewed the ALIGN project to address CCUS issues with solvent research. She presented projects related to decarbonizing the ferroalloy industry, electrochemical production of hydrogen from natural gas, and on the waste-to-energy sector (BioCCS). The Oslo waste-to-energy plant has been modelled with oxy-fuel CO_2 capture. A disruptive CO_2 capture (adsorption) process was reviewed, as Climit aims to develop better than state-of-the-art solvent technology. Additionally, HalZero was reviewed as a mechanism to produce aluminum without carbon emissions. The ACT (accelerating CCS technology) coalition is transitioning to the CETP (Clean Energy Transition Partnership).

Ron Munson took the place of Dan Hancu to present on point-source capture. Munson reviewed the infrastructure bill and Office of Fossil Energy and Carbon Management carbon capture model. The carbon management BIL funds carbon transport, carbon capture, storage, and industrial decarbonization. Billions of dollars are invested into such programs. Several DOE components are looking at efforts to advance capture technology. Point source capture strategic vision involves supporting retrofit of power, net zero, flex power, industrial retrofit, and integrating decarbonized industry plus CCS. FEED studies have played a vital role to the DOE in regard to point-source capture and many have been funded to determine the costs and operations associated with DAC, as well as cryogenic carbon capture at cement plants. There is a necessity to better understand emissions related to capture technology itself. A question was posed during the presentation: Where does the stream of new ideas come from? Munson answered by stating a technology team meets regularly in addition to workshops and requests for information from stakeholders.

Does the United States focus on energy production with regard to CCS, decarbonization, or both?

Both. The United States has a long history of power work, and is still concerned about the development of power, but considers a shift toward natural gas significant to U.S. history as it is the focus of higher carbon capture rates. So, the United States will aim the majority of CCS efforts toward industrial sector instead of power sector.

Technology Scale-up and Commercialization Pathways

Select companies presented from North America and Norway to highlight the troubles with scale up and how they have managed to best navigate the hurdles from moving from bench scale to industrial scale. A common theme was the use of testing centers that are well equipped with instrumentation and analytical capabilities.

North American Companies

ION

Eric Meuleman presented ION's innovations with new solvent standards. The innovations began with ionic liquids, but shifted quickly to amine-based solvents. ION has a strong partnership with DOE and has been awarded $85 million. The new Ice-31 solvent standard allows for low emissions, excellent solvent stability, faster solvent kinetics, and lower energy requirements. These developments were tested at the Technology Center Mongstad and confirm excellent results.

Svante

Claude Letourneau presented Svante's innovations with a solid sorbent. Solid sorbent technology boasts the benefit of 60-second cycle of releasing and capturing CO_2. Svante has found it to be energy efficient with a high selectivity over water with no secondary

emissions. The sorbent technologies lie in a large (on the magnitude of 14 meters in diameter) rotary contactor design. The design allows for continuous catch, release, and cooling cycles, with a replacement of filters every 3 to 5 years.

Norwegian Companies

Aker Carbon Capture

Jon C. Knudsen presented Aker Carbon Capture innovations such as Just Catch 400 carbon capture. Currently, there are seven large-scale plants in delivery. CO_2 streams have been tested with a mobile testing unit, which calls further attention to the problem of impurities in streams as sometimes the tests failed. Test centers, such as the Technology Center Mongstad, are noted as crucial for scale up.

Compact Carbon Capture, Baker Hughes

Torleif Madsen presented compact carbon capture (CCC) commercial technology. Baker Hughes is well-positioned across the whole CCUS value chain. A novel design of the first rotating desorber wheel concept was the initial CCC development, followed by the development of a cross-flow absorber in 2017. The CCC pilot plant has achieved TRL 5 results with a capture rate of up to 95%.

Where are common issues where collaboration between U.S. and Norway can progress carbon capture as an industry? What is needed?

One participant repeated a common point that as much regulatory predictability as possible will encourage market competitiveness.

Another participant stated that the United Kingdom has funded many FEED studies that international communities can learn from. There is an opportunity to take the FEED studies that have been completed and learn from them rather than redoing the work that has already been done.

The last comment on this question was that public relations is now highly important, with headlines focusing on failures. The technology is there—it's no longer an issue of insufficient carbon capture technology—it's a business model issue. Carbon capture is often associated with coal and EOR, which breeds distrust, thus dissociation from fossil fuel industries is necessary.

Test Centers' Roles in Technology Development

Monitoring, Reporting, and Verification for Point Source Capture and Standardized Methods across Pilot Testing and Test Centers

Tiller

Karl Anders Hoff represented Tiller and discussed the full height pilot in operation. The pilot aims to demonstrate and verify the qualification of solvents, such as how they can apply to a range of industrial conditions and long-term operation. Additionally, the pilot involves development of advanced process configurations for low-energy CO_2 capture, dynamic operations of capture with predictive control, simulation models closely integrated with piloting, and in-house modeling and simulations with CO2SIM. Tiller has developed new solvent formulas, and continuously researches amine emissions monitoring and mitigation, and solvent degradation. Tiller recently celebrated 100,000 hours of operation since 2010, and has played a significant role in developing Aker Carbon Capture solvent technology towards full scale. Small-scale full-height plants provide valuable scientific and engineering insights. Further works involve solvent management for long-term operation, CO_2 liquefaction as part of capture system, and further work on process controls.

National Carbon Capture Center

John Northington represented the National Carbon Capture Center (NCCC), which boasts 145,000 hours of carbon capture testing since 2009. The NCCC seeks continuous expansion with flexibility for testing at multiple scales at facilities run on natural gas or coal. Accelerated technology development at NCCC involves over 16 technologies in queue to test with multiple progressing through FEED studies, eight technologies scaled-up, and CO_2 concrete technology commercialization. Lessons learned have been: sample gas treatment is crucially important, understanding analyzer capability to ensure right instrument for analysis is necessary, flue gas source analysis and pre-treatment is necessary, and focus on long-term continuous solvent emission and degradation analysis is necessary. Next steps for NCCC include emissions characterization and reduction, exploring advanced analyzer for solvent degradation/emissions, and consideration of design for flexible multi-stage flue gas washing for emission reduction.

TCM

Ismail Shah presented innovations at Technology Center Mongstad. TCM is the world's largest and most flexible center for developing CO_2 capture technology and a leading competence center for carbon capture that is owned by Gassnova, Equinor, Total Energies, and Shell. TCM has capabilities to measure degradation and emissions from solvents. Two industrial flue sources with different levels of CO_2 at 24/7 operation are currently active, with the possibility to test multiple technologies in parallel—the last step before commercialization. TCM has run several test campaigns related to solvent and emerging technologies.

University of Kentucky

Kunlei Liu represented the University of Kentucky as part of and present coordinator of the international test center network. Liu discussed FEED study projects as a collaborative effort for regulating air pollutants. Various scales of testing are available with a suite of analytical methods to characterize performance. The University of Kentucky, and its associated network, is actively working on standardization for CO_2 stream sampling methods.

SCOPE

Karl Anders Hoff presented the ACT projects: SCOPE. SCOPE is a collaborative project involved in sustainable and cost-efficient amine emission control. Amine-based chemical absorption will play a significant role in decarbonization and it is essential that capture plants are environmentally friendly and well-regulated. The emissions studied by the SCOPE project are connected to volatility of the amine, emissions are often via formation of aerosols, emissions are also possible through the degradation products. SCOPE has six test facilities ranging from small pilots to large demonstration plants. The activities in SCOPE are test campaigns focused on emissions and emission controls, models for design of mitigation options, and improving dispersion models to predict atmospheric chemistry, incldinf environmental impacts. SPRINT is a stakeholder forum on CO_2 capture regulations, developments of best practices for emission control, mitigation of environmental impacts from post-combustion carbon capture plants, and guidance on how to address main knowledge gaps related to emissions.

Hydrogen

Overview, Program Activities, and Updates

National Activities U.S.

Eric miller and Bob Schrecengost presented the national hydrogen-related activities in the United States. Hydrogen is a versatile energy carrier that can be used across many industrial sectors. The DOE hydrogen priorities are low-cost clean hydrogen, cost-efficient safe hydrogen delivery and storage, and enablement of end-use application as scale for impact. The BIL includes $9.5 billion for clean hydrogen, with $1 billion to electrolysis, $0.5 billion for manufacturing and recycling, and $8 billion for at least four regional clean hydrogen hubs. The IRA includes significant tax credits for hydrogen. The Hydrogen Energy Earthshot aims for $1 per 1 kg clean hydrogen in one decade.

The FECM is focused on hydrogen production from fossil resources, waste and available biomass, along with CCUS to achieve net-zero carbon, hydrogen power generation, and energy storage using reversable solid oxide cells. Four pre-commercial hydrogen FEEDs are being conducted. A hydrogen transportation pipeline will become necessary, and FEED studies have been awarded to characterize long-term hydrogen impact on pipeline materials and gas blending, and to characterize various underground storage options.

National Activities Norway

Åse Slagtern represented the Research Council of Norway (RCN) to present the hydrogen-related activities of Norway. Norway is dominantly hydro-electric power; thus, the main driver of CO_2 emissions is industry and transport. Norway is observing a shift in ship power to hydrogen cells as the Norwegian hydrogen strategies advance. 2030 ambitions include hydrogen as an energy carrier established as a real alternative in maritime and good alternative in industry. Research funded by the RCN has involved the production of hydrogen, storage and distribution of hydrogen, use of pure hydrogen in industrial processes, and long-range transport (especially maritime). Enova awards funding for three ammonia ships, and new projects have been launched by Enova to develop hydrogen and ammonia-fueled vessels.

Fionn Iversen presented HyValue, the Norwegian Centre for hydrogen value chain research. The center researches safe and sustainable development of value chains for hydrogen through significant cost reduction of energy loss and emission, cost-efficient solutions, solving technical challenges, improving knowledge in risk assessment, and resolving economic and regulatory barriers for implementation. Research emphasizes novel production, storage and distribution, end-user application, societal impact and embeddedness, and integrating hydrogen value chains.

Steinar Eikaas presented Equinor's strategic ambitions toward net zero in 2050. Today, there are developments that will allow clean hydrogen projects in three to five major industrial clusters. Additionally, by 2035, there will be pipelines constructed to transport 15 to 30 million tons per year.

Hydrogen-Related Issues for Discussion

Nick Barilo presented on hydrogen safety. First, Barilo discussed the impacts that incidents have on industries by pointing to several global examples of incidents that caused deaths. Hydrogen has dangers associated with it, but there is great knowledge surrounding the chemical properties of hydrogen and a large framework for best practices already set in place as the technology advances. It is necessary to make safety a standard and implement regulations, codes, and standards that help bolster public confidence.

Greg Cooney began a presentation on lifecycle assessment (LCA)/carbon footprint of hydrogen production. The IRA incentivizes the production of clean hydrogen. The DOE engaged in a fossil-based H2 study to help form the current considerations of the DOE with respect to hydrogen energy. The IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) has a white paper on version three that is a global effort to facilitate global economy in hydrogen trade. That white paper effort has morphed into ISO 19870. Pradeep Vyawahare took over the presentation to discuss the GREET model and the lifecycle analysis of hydrogen, split into GREET 1 model and GREET 2 model.

Discussion: Areas of Cooperation in Hydrogen

The European view on hydrogen should be further discussed at a later time, as it is very similar to Norway's view. LCA, regulations, and safety are areas where further collaboration should be encouraged. Practically, this collaboration could take place through programs like CETP, as the United States has already put money into programs to encourage collaboration.

Several observations were made by representatives of regulatory agencies during the workshop. First, there is a necessity for a type of manifesto on public engagement and outreach on innovative breakthroughs. Second, there needs to be an economic analysis for secondary markets and identifying price-points for breakthrough thresholds to examine what price hydrogen needs to get to for adoption in various industries. Application of diesel exhaust fluid with selective catalytic reduction in 2008 in the diesel industry is a good example. Lastly, research engagement on outreach strategies that identify social barriers and mitigators or drivers for discovered barriers is necessary.

A representative for the DOE responded to those observations by stating that the DOE is looking toward IPHE for policy guidance. It is important for organizations to communicate collaboratively, and it may be a good idea to encourage a certification program through collaborative development.

The workshops acknowledged that safety and evaluation are important and having a good data-sharing platform is necessary, and not in an ideal state today. A data-sharing discussion should take place in the future.

With the noise around natural hydrogen, is there any consideration of that with U.S. policy?

Colleagues across the technical team of the DOE are excited about natural hydrogen, but it's not well understood, so U.S. policy remains to be seen.

End Day 2

Appendix: Registry

First name	Last name	Affiliation	Country
Mark	Ackiewicz	U.S. Department of Energy	United States of America
William	Aljoe	U.S. Department of Energy	USA
David	Alumbaugh	Lawrence Berkeley National Lab	United States
Matt	Antes	U.S. Department of Energy - FECM	USA
Melissa	Batum	Bureau of Ocean Energy Management (BOEM)	United States of America
Susan	Blevins	ExxonMobil Low Carbon Solutions	USA
Susan	Blevins		
Alex	Bump	University of Texas at Austin	US
William	Christensen	Norwegian Ministry of Petroleum and Energy	Norge
Greg	Cooney	U.S. Department of Energy	USA
Brad	Crabtree	Assistant Secretary, Office of Fossil Energy and Carbon Management, U.S. Department of Energy	USA
Darin	Damiani	US DOE FECM	USA
Noah	Deich	USDOE	
Devin	Dickson	Battelle	
Arne	Dugstad	IFE (Institute fir Energy Technology)	Norway
Fred	Eames	Hunton Andrews Kurth	
Lars Ingolf	Eide	Research Council of Norway	Norway
Steinar	Eikaas	Equinor	USA
Peder	Eliasson		
Andrew	Fishbein	Climeworks	United States
Evan	Frye	U.S. Department of Energy - Office of Fossil Energy and Carbon Management	USA
Sarah	Gasda	NORCE	Norway
Amir	Ghaderi	SINTEF	Norway
Stanislav	Glubokovskikh	Lawrence Berkeley National Laboratory	United States
Bettina	Goertz-Allmann	Norsar	Norway
Dan	Hancu	US DOE	US
Aslak Solvang	Hellestø	Northern Lights JV	Norway
Andrew	Hlasko	U.S. Department of Energy	USA
Karl Anders	Hoff	SINTEF Industry	Norway
Michael	Idziorek	US DOI - Bureau of Safety and Environmental Enforcement	USA
Fionn	Iversen	NORCE Norwegian Research Centre	Norway
Børre	Jacobsen	Northern Lights JV DA	Norway
Rory	Jacobson	DOE	United States
Jon Christopher	Knudsen	Aker Carbon Capture	Norway
Marcus	Koblitz	bp America	United States
George	Koperna	Advanced Resources International, Inc.	United States

First name	Last name	Affiliation	Country
Alex	Krowka	USEA	
Claude	Letourneau	Svante	Canada
Michelle	Littlefield	USEA	
Kunlei	Liu	University of Kentucky/IDEA	United States
Torleif	Madsen	Baker Hughes Compact Carbon Capture	Norway
Ross	Markwort	ExxonMobil Low Carbon Solutions	United States
Timothy	McCune	Bureau of Ocean Energy Management (BOEM)	United States of America
Mark	McKoy	U.S. DOE -- National Energy Technology Laboratory	U.S.A.
Mark	Menezes	USEA	
Erik	Meuleman	ION Clean Energy	USA
Steffen	Møller-Holst	Vice President Marketing - Hydrogen Technologies	Norway
Michael	Moore	US Energy Association	US
Jason	Muller	Equinor	United States
Ron	Munson	NETL/DOE	
John	Northington	Southern Company	United States
Calli	Obern	US Department of Energy	USA
Mike	Olsen	Aker Carbon Capture	United States
Volker	Oye	NORSAR	Norway
Rajesh	Pawar	US DOE - FECM	USA
Michael	Pittman	US DOI, Bureau of Safety and Environmental Enforcement	USA
Aidan	Preston	DOE-FECM (AAAS Fellow)	United States
Philip	Ringrose	Equinor	Norway
Eva	Rodezno	US DOE	US
Katherine	Romanak	The University of Texas BEG	US
Kari-Lise	Rørvik	Gassnova	Norge
Roxane	Roy	Svante	Canada
Robert	Schrecengost	US DOE	USA
Muhammad Ismail	Shah	Technology Centre Mongstad	Norge
Åse	Slagtern	The Research Council of Norway	Norge
Robert	Smith	U.S. DOE/FECM	USA
Aage	Stangeland	special adviser	Norway
Kyrre	Sundseth	SINTEF	Norway
Jørild	Svalestuen	Gassnova	Norge
Grethe	Tangen	SINTEF	Norway
Ivar-Jo	Theien	Innovation Norway	Norway
Ryker	Tracy	Battelle	
Chris	Walker	bp	United States
Andrea	Wilson	U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement (BSEE)	United States

First name	Last name	Affiliation	Country
Armin	Wisthaler	University of Oslo	Norway
Peng	Ye	Equinor	United States
Arne			