Columbia World Projects

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Accelerating Offshore Carbon Capture and Storage

Opportunities and Challenges for CO_2 Removal

Report on October 2020 Workshop

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Columbia World Projects

SUMMARY

In October 2020, Columbia World Projects (CWP) held a 3-day workshop to discuss the challenge of scoping the uncertainties for offshore carbon dioxide (CO_2) capture and mineralization. The workshop is a critical first step in moving potential new and essential technologies towards large-scale implementation. CWP was pleased to help participants envision how they could launch effective demonstration of field projects in the offshore environment.

Climate change, caused by anthropogenic CO_2 and other greenhouse gas emissions, is one of the most urgent and extensive global threats confronting us today. The need to rapidly reduce emissions has prompted growing interest in CO_2 capture and sequestration (CCS). However, there are many technical and non-technical challenges associated with implementing CCS technologies, particularly offshore. These include issues associated with long-term liabilities, various engineering and ecological concerns, as well as public acceptance. Workshop discussions focused on two potential offshore locations where designs for future demonstration projects are being considered.

Accelerating Offshore Carbon Capture and Storage

Opportunities and Challenges for CO_2 Removal

Cascadia Basin

Continental Shelf

Columbia University in the City of New York

Like other climate mitigation activities, offshore CCS poses a dynamic risk management problem. Any potential solution requires an understanding of the uncertainties, its potential for success, required investments, operating costs, regulation, and public acceptance, as well as how all of these factors evolve over time. The CWP workshop covered many of the key technical and non-technical issues associated with large-scale CCS and its technical underpinnings, and assessed the uncertainties in conducting pilot projects at two potential offshore locations – the Cascadia Basin in the northeastern Pacific and the continental shelf along the U.S. Atlantic coastline. These sites have the potential, at scale, to store billions of metric tons of CO_2. Both sites feature sub-seabed basalt rock formations, wherein injected CO_2 may rapidly mineralize and significantly reduce the potential for leakage. Pilot projects at one or both sites could demonstrate a new approach for permanently and safely storing CO_2 that would be replicable around the world. The workshop explored many of the technical, regulatory, and social uncertainties that would be involved in pursuing these projects.

The workshop was coordinated as part of the development of a potential project emerging from the CWP Forum on Decarbonization, with the support of several Columbia University centers and schools including the Earth Institute, Lamont-Doherty Earth Observatory, the Sabin Center for Climate Change Law at Columbia Law School, and the Center on Global Energy Policy at Columbia School of International and Public Affairs and Columbia Engineering, and led by Ken Hnottavange-Telleen of GHG Underground. The workshop convened more than 35 experts from academia, national laboratories, non-governmental organizations, and the private sector (see Appendix 1 for biographies) to characterize and discuss a wide range of issues involved with CCS, renewable energy, and offshore policies.

The workshop consisted of three online sessions, each focusing on the uncertainty in key criteria for project success – what is well known, what is not known, and what still remains to be discovered. The contents of the workshop were developed based on prior scholarship and research. A set of background materials consisting of readings, introductory presentations, academic publications, and technical documents concerning the approach, methodologies, and discussion criteria were shared with all participants prior to the workshop. The agenda of the workshop can be found in Appendix 2. After a discussion led by an expert in the criterion, the relative uncertainties for each were assessed by quantitative polling. All participants provided real-time numerical estimates and comments, or categorical choices, about their assessment of the importance of each criterion.

The first session addressed uncertainties about the two site locations, geology, and *CO_2 sources*. The discussion covered goals for project scaling and developing a common technical vocabulary that might help participants assess variations in project designs and their impacts across different environments. The second session addressed the enabling technologies, those well established and those still developing, the most challenging technological gaps, and the potential for upscaling. The discussion in session two centered on *offshore platforms*, CO_2 capture at industrial facilities and through direct air capture (DAC), CO_2 purity, stream composition, and transportation options. A third session focused on the issues specifically relating to public engagement, permitting, and other regulatory approvals for long-term offshore CCS projects and how these might affect project design, location, scaling, and options for financing – all critical factors that may influence public support for long-term climate solutions. In all sessions, the similarities and distinctions between potential projects on the East and West coasts of North America were considered. Each session concluded with a summary of issues that would need to be addressed in order to implement field demonstrations of these offshore project designs.

Workshop discussions highlighted important focus areas for the future, to reduce project uncertainties, including:

- engineering design, testing, and integration of technologies for CO_2 capture, transport, and subseafloor injection systems;
- demonstrating sustainable CO_2 storage and long-term monitoring in offshore basalt reservoirs;
- testing and deployment of offshore renewable energy resources (e.g., wind);
- exploring policy options to incentivize investment in CCS, particularly for offshore projects;
- developing a legal and regulatory framework for offshore CCS that enables and encourages project development;
- establishing mechanisms for cross-disciplinary engagement to facilitate technical, regulatory, and financial coordination in complex offshore projects; and,
- conducting further research into public perceptions of offshore CCS and how they vary based on project location and design.

Each is an essential step needed to reduce project and financial risks and pave the way for the large-scale infrastructure investments that will be required in the future.

This report summarizes the workshop findings and preliminary outcomes.

MOTIVATION

The carbon storage ***Offshore CO_2 Capture and Mineralization Workshop*** supported by Columbia World Projects aimed to identify requirements and implications (broad versions of costs and benefits) of conducting subsea geological carbon dioxide (CO_2) storage. At its current early stage, the considerations for developing a subsea storage project were designed to embrace a variety of possible CO_2 capture processes, transportation, platform and energy source options, and multiple physical offshore locations. At this broadest level, the workshop considered two coastal environments offshore North America, with CO_2 captured from two different primary sources – industrial facilities (various sectors), and ambient air (DAC, Direct Air Capture). A primary objective was to comprehend the many implications of actual project designs that would hew to specific sets of possibilities for these four comparative cases. For each case, various options for CO_2 transport (e.g., pipeline versus ship), offshore platform design and energy source, and CO_2 injection were considered. Cross-cutting issues related to project financing, regulatory approvals, and social acceptability were also discussed.

The four project designs and locations considered at the workshop are:

- Offshore New York / Jersey (Mid-Atlantic), using industrial-source CO_2
- Offshore New York / Jersey, using direct-air-captured CO_2
- Offshore Washington / British Columbia (Cascadia), using industrial-source CO_2
- Offshore Washington / British Columbia, using direct-air-captured CO_2

In these four cases, the focus was on subsurface geological storage of CO_2 in basalt rock, in contrast to more common sandstone storage reservoirs, for the following reasons:

(1) Basalt is the most globally extensive near-surface rock type; therefore, an actual storage project executed in this rock type would generate knowledge that could be widely applied;

(2) Open spaces, layering, and fractures in basalt offer likely pathways for injected CO_2; and

(3) Basalts have been shown to quickly incorporate injected CO_2 to form new minerals, thus creating a stable solid phase that would neither cause near-term environmental damage nor later escape back into the atmosphere.

In these four cases, the focus was on potential CO_2 storage sites offshore, where extensive basalt deposits occur, but which also offer the following benefits:

(1) CO_2 injection in offshore basalts will avoid potential contamination of freshwater sources (which are generally onshore);

(2) Offshore sites (uncomplicated by onshore land holdings and activities) may offer jurisdictional simplicity; and

(3) Offshore settings may offer unique opportunities for power generation through low-carbon technologies such as wind, solar, wave, and/or tidal.

BACKGROUND

Both the Cascadia and Mid-Atlantic areas have been the subject of previous regional-scale studies concerning their CO_2 storage potential. Considerable research on the basalt reservoirs in the Cascadia area has been conducted; however, information on the basalt reservoirs in the Mid-Atlantic area is known only from indirect methods and regional geologic interpretations.

The Cascadia Basin ridge-flank site is located in water depths of 2600 meters with potential basalt reservoirs located 300-500 meters below the seafloor. Several existing scientific research wells in this area have defined basic properties of the basalt reservoir, such as mineral composition, temperature, permeability, and porosity. The various pores, vesicles, and fractures in basalt provide space where injected CO_2 can collect and mineralize over time. Whether those properties extend laterally is not well known, however. Measured temperatures within the reservoir are warm (60° C), and inferences about their lateral extent and permeability rely heavily on geothermal modeling. Overlying sediments have low permeability and have been shown to be effective in containing the natural hydrothermal flow within basalt layers below.

By contrast, the offshore Mid-Atlantic site is located in water depths of 200 meters with potential basalt reservoirs located 2000 meters below the seafloor. These locations have only been explored using surface geophysical methods, and the offshore basalts in the region have not been drilled or sampled to date. Information about these basalts is based on data from onshore deposits, where known porous and permeable basalt rocks may offer large storage reservoirs. The Mid-Atlantic sites do not likely feature hydrothermal systems, in contrast to those of the Cascadia Basin; the basalt is older, possibly more laterally confined, and estimated temperatures are considerably cooler.

Some of the well-known site attributes that strongly affect project design (e.g., water depth, water and reservoir temperature, distance to industrial-source CO_2) are clearly differentiated between the Cascadia and Mid-Atlantic sites. For other attributes, their effects upon project viability remain unclear.

Similarly, the implications of using CO_2 captured from concentrated industrial sources vs. directly from ambient air (DAC, Direct Air Capture) are not straightforward for either location. The source of CO_2 has a significant impact on the chemistry of impurities, temperature, pressure, and moisture content of the stream. Low moisture content is highly preferred to minimize the corrosive effects of CO_2 on pipelines and drilling equipment. These technical aspects of the CO_2 source and stream processing are important in establishing project uncertainties, particularly for developing technologies such as DAC. Offshore DAC will also require significant power, potentially from renewable wind or wave turbine sources. Although many of these technologies currently exist, or are rapidly developing, technological uncertainties remain about the type of platforms to be used offshore, their depth capacity, longevity, size, and long-term maintenance requirements.

Critical non-technical uncertainties must also be considered, including financial investment needs, long-term liabilities, permitting and other regulatory requirements, and the social acceptance of CCS, in general. Among these, the uncertainties surrounding regulatory permitting and public acceptance of CCS may be most considerable. Regulation of the offshore disposal of CO_2, non-CO_2 contaminants, and ocean jurisdiction at federal, state, and local governmental levels remain unclear. Common public concerns that focus on storage security (i.e., leak avoidance), both for CO_2 transportation and long-term disposal, will require new site monitoring and established safety demonstrations.

WORKSHOP DESIGN

Uncertainty is due mainly to our lack of knowledge (epistemic uncertainty), although natural-system unpredictability (stochastic or aleatory uncertainty) also plays a part. In the context of the large and varied uncertainties associated with offshore CO_2 capture and mineralization, an expert-elicited workshop was organized. The workshop was intended to: (a) identify the major sources of uncertainty for each of the four project designs, and (b) evaluate the identified uncertainties for their relative importance to eventual project success. Results were anticipated to provide guidance on what further work might best be done to reduce uncertainties and thus progress one or more projects toward field engineering and demonstration. This result is similar to what is often expected from a conventional project risk workshop – typically a more concrete exercise that attempts to quantify risks for events that might deviate from well-specified success criteria in an already-determined project. The array of potential risks for any project may result in a very large number of possible scenarios. Therefore, the Uncertainty Scoping Workshop was envisioned as a similar, but broader, effort to characterize the uncertainties in realizing key criteria for each of the four major project designs, amounting to a manageable number of topics to be considered. This approach attempts to estimate the importance or "size" of particular categories of uncertainty, rather than trying to quantify each specific project risk, for the project designs considered.

ESSENTIAL PROJECT CRITERIA

The workshop participants evaluated uncertainties associated with several key project components across the four primary project designs. These components were developed to represent the requirements for funding, construction, and operation of a physical offshore CCS project. Major functional criteria considered at the workshop are listed in Table 1. The major criteria address aspects of a project's physical setting, construction, CO_2 streamflow, social license, regulation, and operation. More detailed "Sub-Criteria" were also developed for evaluation after the workshop (see Appendix 3). In order to move toward implementation, any of the four project designs would need to satisfy detailed criteria and sub-criteria well beyond those considered here. However, many of the high-level criteria and sub-criteria may also apply to other CCS projects and may be useful in future risk assessment efforts related to the implementation of similar technologies.

Table 1: Major functional criteria considered for each project design

Table 1: Major functional criteria considered for each project design

Session	Major Criterion
1a	Sea Surface-Seafloor Site
1b	Sub-Seafloor Site for CO_2 injection and retention
1c	CO_2 sources for project lifespan
1d	CO_2 stream processing to suit pipes and geology
2a	Drilling & completion technology
2b	Transportation of CO_2 stream, source to sink
2c	Offshore platform(s)
2d	Modeling and Monitoring
3a	Permissions, Policy, Public Acceptance
3b	Financing and Liabilities
3c	Management, Maintenance, Personnel

The Major Criteria (listed in Table 1) and uncertainties considered at the workshop were developed to capture important differences between the project designs. These include:

- ***Sub-Seafloor Site***. Understanding of the geologic differences in the rock layers into which CO_2 would be injected, and differences in the level of uncertainty regarding each site's geologic characterization. The two project sites both comprise sub-seafloor basalt reservoirs, but the known information about each site differs substantially.

- ***CO_2 sources*** and ***CO_2 stream processing***. Nature of the CO_2 stream that would arrive at the sub-seafloor injection site. CO_2 sourced via direct-air-capture would be identical for either project design; industrially-sourced CO_2 (including its composition and flow rate) might differ considerably, depending on which specific sources are used, which may in turn differ depending on the storage site chosen.

- ***Drilling & completion technology*** and ***Offshore platforms***. Construction of an offshore CO_2 storage facility in either location may adopt well-established commercial technologies, but differing geography, water depth, sea state, and CO_2 sourcing among the designs could require new technological development.

- ***Permissions, Policy, Public Acceptance***. The governance framework for CCS is highly complex. Multiple laws and regulations could apply to projects. Even if projects are legally permissible, obtaining social license to operate could be difficult. There may be important geographic differences in the legal, policy and social acceptability of projects.

- ***Financing and Liabilities***. Financial risks and liabilities are driven by economic and commercial factors that are currently uncertain for all of the project designs.

WORKSHOP PROCESS

Discussion flow

The workshop was conducted in three two-hour sessions held over one week. The workshop agenda can be found in Appendix 2. During each session, select major criteria in Table 1 were introduced by an expert in that domain, followed by discussion among the participants, both verbally and through online text chat.

In general terms, the first session addressed uncertainties about sub-seabed geology and **CO_2 sources**, the second addressed enabling technologies, and the third addressed programmatic issues such as permissions and financing. Each criterion was discussed in terms of both known and unknown/uncertain aspects within its subject area, and by comparison among the four project designs. A main focus was the importance of particular uncertainties to the eventual success of a project . The major criteria were discussed and evaluated as comprising all relevant sub-criteria. For example, uncertainties pertaining to the specific nature of the basalt reservoirs at the two sites are considered broadly as part of the ***sub-seafloor site*** criteria. After discussion of each criterion, the participants' views were aggregated to characterize the uncertainty in each criterion, for each project design. The mechanics of evaluation and aggregation of the results are described below.

Polling and numerical data

Following discussion of each major criterion, participants were polled for numerically scaled values representing the Uncertainty Scope (Us) and Uncertainty Impact (Ui) with respect to achieving project objectives. The definitions of Us and Ui, as well as the relative 0-to-10 scales for these two values, are provided in the Technical Data Supplement. Here, the product Us * Ui (U) is taken as an overall uncertainty metric. A valuation of U = 0, for instance, represents no impact of that criterion on the project as a whole. Like a value of "risk" that is conceived as the product of probability and impact, the functional value of "uncertainty" for the workshop compares the relative importance of uncertainties among the array of major criteria.

For each major criterion, participants provided paired Us, Ui values by way of a prepared online poll using PollEverywhere software. Each participant responded individually through their personal internet-connected device, providing a Us, Ui pair by clicking a specific point on the displayed graph. Simultaneously, all participants' values were collected on an aggregate graph (e.g., Figure 1), showing the Us,Ui pairs provided by participants in regard to one major criterion for one project design. Since the "uncertainty" metric (U) is taken as the product Us * Ui, uncertainty increases from upper left (blue) to lower right (dark red). Aggregate graphs were shared with the workshop participants only after polling for each criterion was complete so as not to preview results and influence individual assessments.

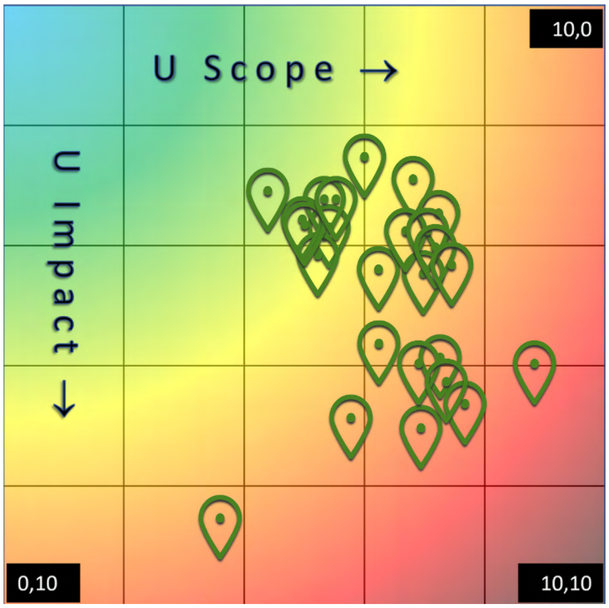


Figure 1. Example aggregate graph of Us,Ui pairs from 25 participants

The workshop addressed 11 major criteria for four project designs, yielding 44 separate polls (44 separate graphs similar to Figure 1). Aggregate numerical data for each of the major criteria are plotted and shown in Appendix 6. Although participants at the workshop numbered 36 in all, each poll typically received between 21 and 28 participant responses since not all participants were present for each discussion. In total, the polling data provided between 1 and 44 Us, Ui pairs from each expert, for a total of 1095 Us, Ui pairs (thus 2190 numerical values of "U"). These 2190 values enable a comparison among the criteria and project designs on the basis of uncertainty, as judged by an invited group of experts most familiar with the pertinent data and unknowns.

DATA SUMMARY AND OBSERVATIONS

Average U values by criterion and project design

Table 2 synthesizes 2190 "U" numerical values from polling, with values averaged across all 21 to 28 poll respondents by major criterion and for the four project designs, that is for both sites and for two CO_2 source types. The criterion with highest average U across all four project designs is reflected at the top of Table 2. Warmer colors and higher values indicate greater uncertainty. The complete dataset and additional presentations/analyses are provided in Technical Data Supplement.

Table 2. Average values of U = Us*Ui

Cascadia Site			*MidAtlantic Site*			***Avg 4***	**Major Criterion ID**	**Major Criterion**
DAC	Indus	Casc Avg	DAC	Indus	MidAt Avg			
37	41	39.1	36	36	36.3	37.7	3b	Financing and Liabilities
27	25	26.2	40	36	38.1	32.1	1b	Sub-Seafloor Site
35	27	30.9	37	27	31.9	31.4	1c	CO_2 sources
26	26	25.6	32	26	28.7	27.2	1a	Sea Surface-Seafloor Site
21	32	26.7	22	33	27.3	27.0	3a	Permissions, Policy, Public Acceptance
37	25	31.0	29	15	22.0	26.5	2c	Offshore platform(s)
19	20	19.1	25	24	24.4	21.8	2d	Modeling and Monitoring
20	19	19.4	18	20	19.3	19.3	2a	Drilling & completion technology
18	22	20.0	15	19	17.1	18.6	2b	Transportation
19	19	19.0	15	16	15.3	17.2	1d	CO_2 stream processing
15	13	13.6	13	10	11.6	12.6	3c	Management, Maintenance, Personnel
24.9	*24.3*	***24.6***	*25.7*	*23.7*	***24.7***	***Avg***		

Specific observations

Specific observations from Table 2 include the following:

- Across the four project designs, *Financing and Liabilities* was polled to have the highest uncertainty (37.7) while Management, Maintenance, and Personnel was polled as least uncertain (12.6).
- Among 44 separate polls, the *Financing and Liabilities* criterion for the Cascadia Industrial project design has the highest uncertainty of all (41).
- Averaging across all criteria, the two site locations are viewed to have nearly the same overall uncertainty (24.6, 24.7).
- For each site location, the DAC source is slightly more uncertain than the Industrial CO_2 source (24.9 vs 24.3; 25.7 vs 23.7).
- For the Mid-Atlantic site, a project design using DAC is viewed as somewhat more uncertain overall (25.7) than a project using Industrial CO_2 (23.7).
- The largest differences in uncertainty between Cascadia and Mid-Atlantic sites occur for *Offshore Platforms* (Cascadia is more uncertain; 31 vs 22) and the *Sub-Seafloor Site* (Cascadia is less uncertain; 26 vs 38).
- Comparing uncertainty for industrial CO_2 vs DAC sources, views on *Offshore Platforms* for DAC are much more uncertain at both the Cascadia (37 vs 25) and Mid-Atlantic sites (29 vs 15).
- Comparing uncertainty for industrial CO_2 vs DAC sources, views about *Permissions, Policy, Public Acceptance* for DAC are much less uncertain at both Cascadia (21 vs 32) and at Mid-Atlantic sites (22 vs 33).

CONCLUSIONS AND NEXT STEPS

Numerous technical and non-technical questions were raised during the workshop discussions, many of which signal uncertainties that will need to be addressed and/or reduced for any project design to proceed. In many instances, these uncertainties result from the fact that an active demonstration of CO_2 injection in offshore basalt rocks has yet to be conducted at either site. With much more existing data in the Cascadia area, the *Sub-Seafloor Site* and *Modeling and Monitoring* criteria at that site are viewed as being less uncertain. New data needs to be gathered in the Mid-Atlantic area to reduce uncertainties in these criteria for those potential basalt reservoirs. For all four potential project designs, uncertainties about the development pathways of new technologies, especially DAC and offshore wind capability, and the effective delivery of CO_2 from source-to-reservoir in a sustainable manner need to be addressed and reduced. The type of offshore platform, capture capacity, and injection equipment used with these technologies, though currently existing, depend critically on the environment in which they are deployed. Each project design must be specifically evaluated for such risks.

Specific non-technical uncertainties regarding the financial drivers, liabilities, regulatory framework, and social acceptability of any of these project designs may be the most important to address. The regulation of offshore CO_2 transport and disposal, when widely implemented, will determine many of the critical constraints on project design, leakage monitoring, and public acceptance. Establishing a clear regulatory framework will, therefore, likely reduce uncertainties. Ultimately, continued research and development and established pilot demonstrations in offshore locations will allow for comprehensive risk assessment of project designs. It will take time to put these pieces in place, however, at any site location and will require several important next steps to reduce uncertainties, including:

- engineering design, testing, and integration of technologies for CO_2 capture, transport, and subseafloor injection systems;
- demonstrating sustainable CO_2 storage and long-term monitoring in offshore basalt reservoirs;
- testing and deployment of offshore renewable energy resources;
- exploring policy options to incentivize investment in CCS, particularly for offshore projects;
- developing a legal and regulatory framework for offshore CCS that enables and encourages project development;
- establishing mechanisms for cross-disciplinary engagement to facilitate technical, regulatory, and financial coordination for complex offshore projects; and,
- conducting further research into public perceptions of offshore CCS and how they vary based on project location and design.

APPENDIX 1. PARTICIPANT BIOGRAPHIES

Edda Aradóttir

Chemist and Reservoir Engineer, Reyk Energy

Dr. Edda Sif Pind Aradóttir is the acting Managing Director of the Department of R&D and Manager of Innovation and Strategic Planning at Reykjavík Energy. She is also the Project Manager of the international CarbFix research project. She has 15 years experience in research related to reservoir management, chemistry and hydrology as well as project management in the field of environmental science. She holds a PhD degree in Reservoir Engineering from the University of Iceland, an MSc degree in theoretical chemistry and BSc degree in Chemical Engineering

Christoph Beuttler

CDR Manager, Climeworks

Christoph Beuttler splits his time between his role as CDR Manager at Swiss Direct Air Capture pioneers, Climeworks and as deputy CEO of Risk Dialogue Foundation St. Gallen, a Swiss NGO, where he is advising institutions such as the Swiss Federal Office of the Environment on climate risks and CDR/Negative Emissions. He is also a visiting lecturer in Risk Perception and Communication in Science and Policy at the Swiss Federal Institute of Technology (ETH) in Zürich. He was educated in Heidelberg and London. His background is in Economics, Management and Sustainability.

Alain Bonneville

Laboratory Fellow, Energy and Environment Directorate, Pacific Northwest National Laboratory (PNNL)

Dr. Bonneville is a geophysicist with expertise in geological storage of CO2, geophysical monitoring techniques (gravity and muography) and geothermal energy. Between 2009 and 2013, he led the PNNL Carbon Sequestration Initiative. Prior to this role, he was a full Professor of Geophysics and Vice Director of the Institut de Physique du Globe de Paris (IPGP). In 2003, Bonneville created a research program on geological sequestration of CO2 funded by TOTALand Schlumberger that established IPGP as a major contributor of fundamental research on this subject in France and Europe. At the same time, he led the European Marie Curie Research Training Network on Greenhouse Gas Removal Apprenticeship and Student Program (GRASP: 14 academic and industrial institutions in 7 countries, 35 PhD students and Post-Docs).

Pat Brady

Senior Scientist of Advanced Nuclear Technologies, Sandia Natioal Laboratories

Pat Brady is a Senior Scientist at Sandia National Laboratories and has authored or co-authored several dozen peer-reviewed journal articles, books, book chapters, and 20 patents, in the fields of geochemistry, climate change, water treatment, enhanced oil recovery, and nuclear waste disposal. His PhD from Northwestern University was on silicate weathering; his Post-Doc from ETH-EAWAG, Switzerland was on silicate weathering and climate change.

Curran Crawford

Professor, University of Victoria

Dr. Crawford works on uncertainty quantification and multidisciplinary optimization techniques applied to energy systems design. His group's work spans from wind (including floating, airborne variants), tidal and wave energy, through to energy storage technologies and electrified transportation to enable renewables integration on- and off-grid. He leads the engineering systems design aspect of the Solid Carbon project, applying his groups methods to optimization of renewable powered, offshore DAC systems design for CCS and CCUS.

Greg Dipple

Professor, Department of Earth, Ocean and Atmospheric Sciences, University of British

Columbia

Gregory Dipple is Professor of Geological Sciences at the University of British Columbia. He studies the processes of, and driving forces for, mineral-fluid reactions, including those that modulate long-term climate through chemical weathering. He has published extensively on fluid-rock interactions from the deep Earth to its surface. Through field, experimental, and modeling studies, he and his students and Post-Docs have demonstrated that weathering of alkaline mine wastes are vastly accelerated over background weathering rates and impact the short-term carbon cycle. Current work focuses on industrial control of these processes for carbon capture, utilization and storage. Dipple has worked at The University of British Columbia since 1992 where he has served as a Department Head, Associate Dean, and a Research Unit Director. Currently he is enjoying being just a Professor.

Tim Dixon

General Manager, IEA Greenhouse Gas R&D Program (IEAGHG)

Tim Dixon is the General Manager for the IEA Greenhouse Gas R&D Program (IEAGHG). He is responsible for managing the R&D program, ensuring that IEAGHG activities provide the technical evidence-base to support Carbon Capture and Storage (CCS) development and deployment, including the IEAGHG technical studies, research networks, GHGT conferences, and Summer Schools, and for inputting evidence-base to international regulatory and policy developments. He is chair of several international committees on CCS, including the GHGT Conference series' Technical Programme Committee, the IEAGHG Monitoring Network, and the Offshore CCS workshop series. He sits on advisory committees for several CCS R,D&D projects. He is also a Director on the Board for The International CCS Knowledge Centre in Regina, Canada, and was a founding Board Member of the UK CCS Research Centre. He is an Honorary Senior Research Fellow at the Bureau of Economic Geology, University of Texas in Austin, and an Honorary Lecturer at the School of Geosciences at University of Edinburgh. He has a BSc in Applied Physics and an MBA, and is a member of the UK Institute of Physics, UK Energy Institute, UK Environmental Law Association, and an expert reviewer for IPCC.

Adrienne Downey

Principal Engineer, Offshore Wind, NYSERDA

Adrienne Downey (B.Eng. M.Sc.) is the Principal Engineer for Offshore Wind with the New York State Energy Research and Development Authority (NYSERDA)'s Large-Scale Renewables Team. In this role, she leads New York State's offshore wind program, including the recent procurement of 1,696MW, economic development programs, and NYSERDA's stakeholder engagement efforts that will each be critical in delivering the state's nation-leading commitment of 9GW of offshore wind by 2035. She comes to NYSERDA with over a decade's experience in on-shore wind and a consulting practice in climate adaptation and resiliency projects. She has worked internationally in Europe and across Canada across a range of roles in industrial and production engineering, supply chain localization and development strategy, operations management, business development, and policy and government affairs.

Andrew Fisher

Professor, University of California, Santa Cruz

Andrew Fisher is a Professor of Earth and Planetary Sciences at the University of California, Santa Cruz, where he is also affiliated with departments of Environmental Studies, Microbiology and Environmental Toxicology, and Ocean Sciences. He is the UCSC Director for UC Water, co-PI for the Center for Dark Energy Biosphere Investigations, and founder of The Recharge Initiative, a focused effort to protect, enhance, and improve the availability and reliability of groundwater resources. Fisher has authored or co-authored more than 200 articles, book chapters, reports, and other documents, and supervised 24 graduate students and more than 50 undergraduate student researchers. Fisher teaches classes in geology, hydrology, groundwater, and groundwater modeling, and conducts research on: geothermics, marine hydrothermal circulation, surface water – groundwater interactions, managed recharge, coupled flows (fluid-heat-solutes), water quality, and development of new hydrologic tools and techniques. He has served on numerous technical advisory committees for agencies, municipalities, and NGOs. He earned a B.S. in Geology from Stanford University, and a PhD. in Marine Geology and Geophysics from the University of Miami. He is a Fellow of the American Geophysical Union, the Geological Society of America (GSA), and the American Association for the Advancement of Science, received the O. E. Meinzer Award in Hydrogeology from the GSA, and is a two-time recipient of Excellence in Teaching Awards from UCSC.

Sarah Forbes

Scientist, United States Department of Energy

Sarah M. Forbes is a scientist in the Fossil Energy Office of Clean Coal and Carbon Management Division of Systems, Economic and Environmental Analysis. She began her career at the National Energy Technology Laboratory, working on Carbon Capture and Storage (CCS) during the program's formative years.

Julio Friedmann

Senior Research Fellow, Center on Global Energy Policy, SIPA, Columbia University

Julio Friedmann is one of the most widely respected experts in the U.S. on carbon removal, CO2 conversion and use, and carbon capture and sequestration. He is a Senior Research Scholar at Columbia University's Center on Global Energy Policy, where he leads a major research initiative to study the public policy, financial and economic aspects of carbon management.

Michael Gerrard

Andrew Sabin Professor of Professional Practice, Columbia Law School, Columbia University

Michael B. Gerrard, Andrew Sabin Professor of Professional Practice at Columbia Law School, teaches courses on environmental law, climate change law, and energy regulation, and is director of the Sabin Center for Climate Change Law. He was the chair of the faculty of Columbia University's renowned Earth Institute from 2015 to 2018. From 1979 through 2008, he practiced environmental law full time in New York, most recently as partner in charge of the New York office of Arnold & Porter. Gerrard was the 2004-2005 chair of the American Bar Association's 10,000-member section of environment, energy, and resources. He has served on the executive committees of the boards of the Environmental Law Institute and the American College of Environmental Lawyers. Several independent rating services ranked Gerrard as the leading environmental lawyer in New York and one of the leading environmental lawyers in the world.

David Goldberg

Associate Director of Marine/Large Programs, Lamont-Doherty Earth Observatory, Columbia University

David Goldberg is a Lamont Research Professor and his interests focus on the integration of different technologies and cross-disciplinary approaches to develop achievable climate solutions. Goldberg received his undergraduate and MS degrees in earth and planetary sciences from the Massachusetts Institute of Technology, and his PhD in geophysics and an MBA from Columbia University. He serves as a core faculty member for the Lenfest Center for Sustainable Energy at Columbia and an Associate Director of the Earth Institute's Lamont-Doherty Earth Observatory, Columbia University.

Geoff Holmes

Regulatory Engagement, Carbon Engineering

Geoff Holmes has worked on DAC both academically and at CE since inception. His work has touched on technology design, carbon accounting, and on different DAC facility configurations and their interaction with markets and policies.

Rory Jacobson

Graduate Student, Yale School of Forestry and Environmental Studies (FES), Yale University

Rory Jacobson is an independent consultant pursuing a Master's Degree at the Yale School of Forestry and Environmental Studies (FES). He is a graduate of UC Berkeley's College of Natural Resources, with a focus on U.S. environmental policy. Previously, Jacobson served as a Senior Policy Advisor at Carbon180, where he worked to develop RD&D policies to support the responsible deployment of negative emissions technologies. During summer of 2020, he was a summer research fellow at NRDC where he researched policy strategies for direct air capture technologies. He is interested in policy development and analysis for nature-based climate solutions and negative emissions technologies (NETs).

Noah Kaufman

Research Scholar, Center on Global Energy Policy, SIPA, Columbia University

Noah Kaufman is an Economist, leads research focused on climate change policies, and teaches a course on Energy Decarbonization. Under President Obama, he served as the Deputy Associate Director of Energy & Climate Change at the White House Council on Environmental Quality. At the World Resource Institute, Kaufman led projects on carbon pricing, the economic impacts of climate policies, and long-term decarbonization strategies. Previously, he was a Senior Consultant in the Environment Practice of NERA Economic Consulting. He received his BS in Economics from Duke University, and his PhD and MS in Economics from the University of Texas at Austin, where his dissertation examined optimal policy responses to climate change.

Dennis Kent

Senior Research Scientist & Professor Emeritus, Paleomagnetics Lab, Lamont-Doherty Earth Observatory, Columbia University

Dennis V. Kent is Adjunct Senior Research Scientist at Lamont-Doherty Earth Observatory of Columbia University and Distinguished Professor Emeritus at Rutgers University. He is an author of more than 300 widely cited journal and book articles dealing with paleogeography, paleoclimate, and the long-term carbon cycle, the tempo of geomagnetic polarity reversals, and other aspects of Earth magnetism. He is a member of the National Academy of Sciences and is a fellow of the Geological Society of America, American Geophysical Union (AGU), American Association for the Advancement of Science (AAAS), and the American Academy of Arts and Sciences. Kent was awarded the Arthur L. Day Medal from the Geological Society of America, the Vening Meinesz Medal from Delft University in Holland, the Petrus Peregrinus Medal from the European Geophysical Union, the William Gilbert Award from AGU, and received an honorary doctorate from the Sorbonne-Institut de Physique du Globe de Paris. He has served on the governing boards of the Joint Oceanographic Institutions and Integrated Ocean Drilling Program Management International; as president of the Geomagnetism & Paleomagnetism Section of AGU; as elected member-at-large of the section on Geology and Geography of AAAS; and on the advisory board of the Elsevier journal Earth and Planetary Science Letters. He received an undergraduate degree in Geology from the City College of New York and his PhD in Marine Geology and Geophysics from Columbia University.

Don Lawton

Faculty Professor, University of Calgary

Don Lawton has a PhD and B.Sc. (Hon.) from the Department of Geoscience at Auckland University. He is also an Associate Director of the Consortium for Research in Elastic Wave Exploration Seismology (CREWES) and the Director of the Fold-Fault Research Project (FRP) for Carbon Management Canada. In 2011, he led a team from the University of Calgary and CREWES to New Zealand for seismic imaging below the City of Christchurch following a devastating earthquake there. Lawton held the Chair in Exploration Geophysics between 2002 and 2013. He has been an Editor of the Canadian Journal of Exploration Geophysics, and was a recipient of a Meritorious Service Award from the Canadian Society of Exploration Geophysicists (CSEG) in 1996 and the CSEG Medal in 2000. He has been a member of SEG, AAPG, EAGE, CSEG, CSPG, ASEG, and APEGGA and has authored or co-authored over 500 peer-reviewed research publications in the field of Geophysics.

Christine McCarthy

Associate Research Professor, Lamont-Doherty Earth Observatory, Columbia University

Christine McCarthy is an experimentalist studying microstructure effects on physical properties of earth and planetary materials. She is the Lead PI on a new multi-disciplinary project exploring the kinetics and feedbacks of carbon mineralization of mantle peridotite.

Tip Meckel

Senior Research Scientist, Gulf Coast Carbon Center, The University of Texas at Austin

Tip Meckel is a Senior Research Scientist investigating geologic carbon storage for the Bureau of Economic Geology at The University of Texas at Austin. During his 15 years with the Gulf Coast Carbon Center at the Bureau he has led research focusing on geologic characterization, structural geology, monitoring design, and pressure evolution for CO2 injections. He has been directly involved with many large-scale field demonstration projects funded through the DOE-NETL Regional Carbon Sequestration Partnerships. After early exposure during the FRIO tests east of Houston in 2006, he co-directed the research program for the SECARB CO2-EOR demonstration project in Cranfield, Mississippi, and currently leads the research initiative to identify offshore sequestration potential in the Gulf of Mexico with focus on capacity assessment and high-resolution 3D marine seismic monitoring technologies. Meckel works closely with offshore CCS developments in Japan and the North Sea. He was a contributor to the 2019 National Petroleum Council study on CCUS, and participated in the formation of the Society of Petroleum Engineer's Storage Resource Management System (SRMS). Since 2008 he has been PI or Co-PI on 16 CCS grants totaling over $70 million dollars. Meckel received his PhD from UT Austin, and MS from Univ. MT.

Kate Moran

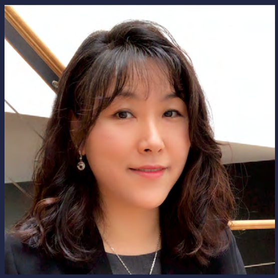
President and CEO, Ocean Networks Canada

Kate Moran is the President & CEO, Ocean Networks Canada. Her previous appointment was Professor and Associate Dean at the University of Rhode Island. From 2009 to 2011, Moran was seconded to the White House Office of Science and Technology Policy where she served as an Assistant Director and focused on Arctic, polar, ocean, the Deepwater Horizon oil spill, and climate policy issues. Moran is active in public outreach on topics related to the Arctic, ocean observing, and climate change.

Stephanie Nitopi

Founder & Managing Director, CarbonSNK LLC

Stephanie Nitopi completed her PhD in Chemical Engineering at Stanford University studying how to convert carbon dioxide into valuable products such as chemicals and fuels with the aid of electricity. Specifically, her research focused on understanding the various factors that impact the reaction efficiency and selectivity when using copper catalysts. This work has led to key insights that will help guide the continued development of catalyst materials and reactor systems that can effectively recycle carbon emissions into useful products. Throughout her PhD, she immersed herself in the rich, interdisciplinary energy ecosystem at Stanford in order to learn how to critically evaluate clean energy technologies and link science to policy, research to practical application, and innovation to scale-up. Nitopi is passionate about accelerating the transition to a more sustainable global energy economy through the co-evolution of energy technology, policy, and finance. She is currently Founder & Managing Director of CarbonSNK LLC., which provides independent consulting, research, and analysis related to carbon capture, use, and storage (CCUS) technology, policy, and innovation.



Ah-Hyung Alissa Park

Director of the Lenfest Center for Sustainable Energy, Earth Institute, Columbia University

A.-H. Alissa Park is the Lenfest Chair in Applied Climate Science of Earth and Environmental Engineering & Chemical Engineering at Columbia University in the City of New York. She is also the Director of the Lenfest Center for Sustainable Energy at the Earth Institute. Her research focuses on sustainable energy conversion pathways with emphasis on integrated carbon capture, utilization and storage (CCUS). The current efforts include the fundamental studies of chemical and physical interactions of natural and engineered materials with CO2 such as the development of novel nano-scale hybrid materials for integrated CO2 capture and conversion. Founded on these new materials and reaction schemes, Park group is also working on Direct Air Capture (DAC) of CO2 and Negative Emission Technologies (NETs). Her group develops sustainable chemical and materials synthesis pathways using CO2, biomass and renewable energy, while minimizing environmental impacts. Her recent work innovatively integrates CO2 utilization and materials distillation schemes based on unconventional resources such as iron and steel slag and electronic wastes to recover rare earth elements and valuable metals while synthesizing greener construction materials. Park received a number of professional awards and honors including the Mid-Career Faculty Award at Columbia University (2020), U.S. C3E Research Award (2018), PSRI Lectureship Award in Fluidization at American Institute of Chemical Engineers (2018), American Chemical Society Energy and Fuels Division - Emerging Researcher Award (2018), International Partnership Award for Young Scientists of Chinese Academy of Sciences (2018), Janette and Armen Avanessians Diversity Award at Columbia University (2017), American Chemical Society WCC Rising Star Award (2017), James Lee Young Investigator Award (2010) and the National Science Foundation CAREER Award (2009). Park also led a number of global and national discussions on CCUS including the Mission Innovation Workshop on Carbon Capture, Utilization and Storage (2017) and the National Petroleum Council CCUS Report (2019). She is a fellow of the American Chemical Society and the Royal Society of Chemistry.

Joseph Gerard Paul

Chief Investment Officer—US Large Cap Value, Alliance Bernstein

Joseph Gerard Paul was appointed Chief Investment Officer for US Large Cap Value Equities in 2009 and has served as Head of Strategic Equities since 2014. He has also served as CIO of the Advanced Value Fund since 1999. Paul was previously CIO of Small & Mid-Cap Value (2002–2008) and co-CIO of Real Estate Investments (2004–2008). Additionally, he was director of research for the Advanced Value Fund for two years. In that role, Paul was instrumental in the genesis of the Advanced Value leveraged hedge fund. He joined AB in 1987 as a Research Analyst covering the automotive industry, and was named to the Institutional Investor All-America Research Team every year from 1991 through 1996. Before joining the firm, Paul worked at General Motors in marketing and product planning. He holds a BS from the University of Arizona and an MS from the Massachusetts Institute of Technology's Sloan School of Management.

Meghan Paulson

Director - Observatory Digital Operations, Ocean Networks Canada

Prior to joining Ocean Networks Canada in the Spring of 2020, Meghan Paulson spent 20+ years working in the energy industry as an engineer and manager in Texas and Louisiana with a focus on drilling and completing exploration and production wells. The energy industry projects included onshore and offshore wells domestically and internationally with a most recent focus on the design and execution of drilling complex (extended reach, deepwater, high temperature / high pressure) wells. In addition to the energy industry, Paulson has been involved in scientific drilling expeditions including Ocean Drilling Program Leg 178 (Antarctic Peninsula) and the Lake Malawi Drilling Project. She holds a BSc degree in Civil Engineering from Dalhousie University and a MSc in Ocean Engineering from the University of Rhode Island.

Philip Ringrose

Professor, Equinor Research Center

Philip Ringrose is a specialist in CO2 storage and reservoir geoscience at the Equinor Research Centre, Trondheim, Norway. He is also Adjunct Professor in CO2 Storage at the Norwegian University of Science and Technology (NTNU). He has published widely on many aspects of low-carbon energy, reservoir geoscience and fluid flow in rock media.

Terre Satterfield

Professor, Equinor Research Center

An anthropologist by training and an inter-disciplinarian by design, Satterfield's work concerns sustainable development in the context of debates about cultural meanings, environmental values, perceived risk, environmental and ecosystem health. Difficult environmental policy dilemmas and the qualitative and quantitative methods that might resolve these are of particular interest. Locally, her work pertains to First Nations interest in land management, oil and gas development, and regulatory contexts. Globally, her research incorporates biodiversity management and politics, and the perceived risk of new technologies (biotechnology, fracking and nanotechnology). She is also a board member or research scientist for several international initiatives that seek to better integrate social science research into policy analysis normally led by the natural and engineering scientists.

Todd Schaef

Surface Energy Systems subsector manager, PNNL

Todd Schaef has been a staff member at PNNL for over 27 years and has attained the position of Senior Research Scientist (IV). He is a team lead in the Geochemistry Group, Subaccount Manager for the fossil energy sector subsurface portfolio, and he has served as Principal Investigator, Co-Principal Investigator, and Project Manager on a diverse range of projects funded by the U.S. Department of Energy's (DOE) Office of Fossil Energy, Office of Energy Efficiency and Renewable Energy, and Solar Energy Technologies Office.

Brian Skeels

Senior Technical Advisor, TechnipFMC

Brian Skeels has 40 years of experience in subsea completion and pipeline design and installation. 5 Years with Exxon Production Research Company working on Exxon's famous SPS and UMC subsea systems, and the rest with TechnipFMC. As a TechnipFMC Senior Technical Advisor, he serves as a Technical Advocate for new technologies and strategic planning specialist for frontier technologies, HPHT, and remote well intervention, including efforts delving into subsea systems engineering and field architecture, riser and riserless well intervention, ROV interfaces, remote robotics technology, hydrate remediation, and well plug & abandonment programs. He has been part of API's Upstream Standards for 35 years and currently serves on API Subcommittee 17 executive committee. He served as task group chair for 17G on subsea intervention systems, co-chairs 17D on subsea tree and wellhead equipment, and chairs 17TR8 for HPHT equipment design. He also has served on several Industry and Professional Society conference program boards.

Angela Slagle

Research Scientist, Lamont-Doherty Earth Observatory, Columbia University

Angela Slagle is an experienced research scientist with a demonstrated history of working in academic research and scientific ocean drilling. She is skilled in Well Logging, Earth Science, Geophysics, Marine Geology, Geology, and Program Management. She is a strong research professional with a PhD focused in Marine Geology & Geophysics from Lamont-Doherty Earth Observatory of Columbia University. She also has a joint position with the International Ocean Discovery Program (IODP).

Jessica Stigant

Associate Director of Government Relations and Partnerships, Ocean Networks Canada

Jessica Stigant is Ocean Networks Canada's (ONC) Associate Director, Government Relations and Partnerships. Since 2012, she has engaged with external stakeholders, including government and industry partners, NGOs, Indigenous communities, and potential donors. From her experience, successful and mutually beneficial partnerships are a result of practiced and respectful interactions between stakeholders. As a member of the ONC team, Stignant provides advice and expertise regarding ONC's liaisons with key external stakeholders. Her experience and skill allow her to successfully manage projects, partnerships and relationships to meet strategic goals, and implement comprehensive outreach programs.

Jessie Stolark

Public Policy & Member Relations Manager, Carbon Capture Coalition

Jessie Stolark is the Public Policy & Member Relations Manager for the Carbon Capture Coalition, a nonpartisan collaboration of 80+ businesses and organizations building federal policy support for economy-wide deployment of carbon capture, transport, use, removal and storage. In her most previous position, Jessie was a Policy Advisor for Third Way where she managed the Climate and Energy Program's carbon capture and industrial decarbonization portfolio. She holds a Master's degree in Applied Geosciences.

Lisa Suatoni

Deputy Director of the Oceans Division, NRDC

Lisa Suatoni is the Deputy Director of the Oceans Division at the Natural Resources Defense Council. She specializes on the intersection of science and policy, as it applies to ocean conservation. Suatoni currently focuses on the interface of marine and climate policies, working to adapt marine policies to better address the impacts of climate change, and working to ensure the Ocean is well integrated into climate policies. Suatoni has also worked to promote sustainable fisheries. She has a PhD. in Ecology and Evolutionary Biology from Yale University. She is also the Timothy B. Atkeson Environmental Lecturer in Law at Yale Law School, where she co-directs the Yale Environmental Protection Clinic.

Devin Todd

Researcher-in-Residence, Pacific Institute for Climate Solutions

Devin Todd joins the Pacific Institute for Climate Solutions (PICS) as a Researcher-in-Residence focusing on Negative Emissions Technologies (NETs). Devin is excited to be part of the PICS Theme Partnership Program on Solid Carbon, which investigates renewable-powered direct air capture of CO2 combined with permanent geosequestration in offshore basalt formations. Prior to joining PICS, he worked with start-ups and investors to advance and triage their cleantech projects. He brings practical know-how and scientific depth to R&D – with an aim on early stage feasibility and technoeconomics of novel technologies. He holds a PhD and a BASc in Mechanical Engineering from UBC.

Sarah Wade

Principal, WADE LLC

Sarah M. Wade is the Principal of a small energy and environmental consulting firm she founded in 2010. She has more than 30 years experience in environmental regulation and policy. Since 2000, her primary work has been related to the development and deployment of carbon capture and sequestration (CCS) technologies including public acceptance, regulations, and policy frameworks.

Romany Webb

Senior Fellow, Sabin Center for Climate Change Law, Columbia University

Romany Webb is a Senior Fellow at the Sabin Center for Climate Change Law, where she researches legal and policy tools can be used to reduce greenhouse gas emissions and promote carbon sequestration. Much of her research focuses on the intersection of climate and energy, looking at options to minimize the climate impacts of energy development. Prior to joining the Sabin Center, Webb worked at the University of California Berkeley Energy and Climate Institute, researching executive authority to combat climate change. She also completed a fellowship with the Kay Bailey Hutchison Center for Energy, Law, and Business at the University of Texas at Austin, where she researched energy policy. The fellowship followed several years working in private practice in Sydney, Australia.

APPENDIX 2: WORKSHOP AGENDA

Columbia World Projects

RISK WORKSHOP ON OFFSHORE STORAGE OF CARBON DIOXIDE

October 14, 19, and 21, 2020

11:00am-1:00pm Eastern

Wednesday, October 14	Monday, October 19	Wednesday, October 21
Site location(s) Subsurface storage CO2 sources and processing	Drilling and transport technologies Platform design and energy Monitoring/modeling	Policy, permissions, and public acceptance Financing and liabilities Management, maintenance, and personnel

APPENDIX 3. MAJOR AND SUB-CRITERIA FOR EACH PROJECT DESIGN

Table 1-S: Major and Sub-Criteria for each project design

Seq	Major Criterion	SubCriterion
1a1	Sea Surface-Seafloor Site	Physical suitability
1a2		Natural hazards
1a3		Accessibility
1a4		Energy inputs, GHG footprint, LCA
1b1	Sub-Seafloor Site for CO2 injection and retention	Reservoir porosity, permeability, and thickness
1b2		Confining layers and structures
1b3		Geochemistry for mineralization
1b4		Geological representativeness; usefulness as pilot
1c1	CO2 sources for project lifespan	Industrial source: Flow rate and total mass
1c2		Industrial source: Contractual availabiity
1c3		Industrial source: Composition
1c4		Industrial source: Energy, GHG, LCA
1c5		DAC source: Flow rate and total mass
1c6		DAC source: Contractual availabiity
1c7		DAC source: Composition
1c8		DAC source: Energy, GHG, LCA
1d1	CO2 stream processing to suit pipes and geology	Technical feasibility / readiness
1d2		Processing-plant location
1d3		Material inputs
1d4		Energy inputs, GHG footprint, LCA
1d5		Capital Cost
1d6		O&M Cost
2a1	Drilling & completion technology	Technical feasibility / readiness
2a2		Completion integrity and durability
2a3		Cost (capital + O&M)
2b1	Transportation of CO2 stream, source to sink	Technical feasibility / readiness
2b2		Route feasibility
2b3		Acceptability/permitting
2b4		Cost (capital + O&M)
2c1	Offshore platform(s)	Technical feasibility
2c2		Energy inputs, GHG footprint, LCA
2c3		Acceptability/permitting
2c4		Cost (capital, O&M)
2d1	Modeling and Monitoring	Plume location mapping
2d2		Plume location prediction
2d3		Induced seismicity (m&m, not causation)
2d4		Leakage (m&m, not causation)
2d5		Cost (capital, O&M)
3a1	Permissions, Policy, Public Acceptance	Rights to surface sites and pore space
3a2		Permits to drill, construct, inject, etc.
3a3		Energy inputs, GHG footprint, LCA
3a4		Public acceptance
3b1	Financing and Liabilities	Capital for construction and debt service
3b2		Income (C storage credit, service fees, product sales ...)
3b3		Liability/Insurability
3c1	Management, Maintenance, Personnel	Know-how and Staffing to BUILD
3c2		Know-how and Staffing to OPERATE
3c3		Know-how and Staffing to MANAGE

ADDITIONAL READINGS

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