I-WEST

Intermountain West Energy Sustainability & Transitions

WORKSHOP SUMMARY

The Direct Air Capture Technical Workshop

Virtual workshop held January 19, 2022

WORKSHOP FACILITATORS

Stephanie Arcusa (sarcusa@asu.edu)
William Brandt (bill.brandt@asu.edu)
Jacob Moore (jacob.moore@asu.edu)
Robert Page (encanto24@me.com)
Sourabh Patil (spatil30@asu.edu)
Vishrudh Sriramprasad (vsriramp@asu.edu)

I-WEST PRINCIPAL INVESTIGATOR

Rajesh Pawar
(rajesh@lanl.gov)

I-WEST PROJECT MANAGER

Rachel Atencio
(Rcatencio@lanl.gov)

SUBMITTED TO

U. S. Department of Energy
Office of Fossil Energy and Carbon Management

February 25, 2022

LA-UR-22-21599

Summary of Workshop on Direct Air Capture in the I-WEST Region

Direct air capture (DAC) has been identified as an important technology to achieve carbon neutrality goals in the I-WEST region. DAC removes carbon dioxide (CO_2) directly from the atmosphere, typically using blowers or fans, chemically engineered sorbents, and temperature or pressure differentials. This workshop engaged DAC technology experts, carbon removal startup CEOs, consulting groups, and tribal energy experts to gain a holistic understanding of the DAC landscape.

The primary goal of the workshop was to introduce DAC to the stakeholders of the I-WEST region, explain how the current landscape will evolve over the next 5, 10, and 15 years. The specific objectives of the workshop were:

- To define and describe direct air capture technology, its benefits, limitations, and challenges
- To establish the various potential opportunities for the captured carbon from DAC facilities in sequestration and utilization
- To identify the ways in which DAC can assist and hinder the surrounding communities through job creation and land use
- To understand the current economic and political landscape around DAC
- To connect with stakeholders in the I-West region who are interested in DAC as carbon management tool

The four-and-a-half-hour workshop, which was held virtually due to COVID restrictions, was by invitation only. The I-WEST team identified stakeholders involved in existing or emerging direct air capture projects who would be able to provide insights for formulating the I-WEST roadmap relative to the questions above. The workshop included over 130 participants including stakeholders from over 40 different organizations active in CCUS the region (section 1.1).

The format of the workshop was centered around three moderated panel discussions. Prior to the round tables, there was a Q&A on DAC technology with Dr. Klaus Lackner. The first panel focused on the various potential end-uses of carbon dioxide after it was captured by a DAC device including sequestration, fuel production, and alcohol production. The second panel focused on industry adoption of DAC from the perspective of consulting firms and other large companies looking to achieve carbon-neutrality through carbon removal methods. The third, and last panel focused on the role that DAC can play in creating jobs specifically in the Intermountain west region, and how to create those jobs in an equitable and environmentally just way. After the three panel discussions, the workshop concluded with two brief presentations addressing the economics of DAC and the current policy landscape around it. A workshop agenda is presented in section 1.2. The moderators for each session focused discussion around a set of themes for each roundtable (section 1.3). Questions of interest in each theme were discussed with the participants prior to the workshop. During roundtables, the moderators provided a short introduction to each session and then facilitated dialog, which included Q&A from attendees and content provided in the chat. Key takeaways from the workshop are summarized in Section 1.4.

1.0 Details on the Workshop

1.1 Workshop Attendees

Stakeholders

Last Name	First Name	Company Name	Job Title
Carr	Bonnie	AECOM	Chief Process Engineer
Gina	Fernandez	AECOM	Director of Engineering
Taylor	Kevin	AECOM	Senior Process Engineer
Dahlgren	Eric	Aircela	CEO
Lowndes	Jonny	Aircela	Head of Customer and Market Strategy
Gregovich	Andrew	Anthropocene Geoscience	Founder
Prifti	Algert	Black & Veatch	CCUS Solutions Portfolio Manager
Vranicar	Mark	Black & Veatch	Decarbonization Proposal Manager
Baker	Kate	Blue Cross Blue Shield of AZ	Retired VP & Treasurer
Azarabadi	Habib	Boston Consulting Group	Senior Knowledge Analyst
Dewar	Alex	Boston Consulting Group	Senior Director
Austell	Mike	Carbon Collect Inc	VP Engineering
Minor	Peter	Carbon180	Director of Science & Innovation
Otte	Chris	CIBC	Managing Director
Balsamo	Robert	CIBC	Exec Director
Beck	Bryce	City of Sedona	Sustainability Coordinator
Alatorre	Ramon	City of Flagstaff, AZ	Climate and Energy Coordinator
Pedrotty	Mark	co2rescue	President
O'Morain	Pol	Carbon Collect Inc	

Stakeholders (continued)

Last Name	First Name	Company Name	Job Title
Eisemann	Maria	Colorado Energy Office	Senior Transportation Policy Analyst
Gadikota	Greeshma	Cornell University	Assistant Professor
Karner	Don	Electric Applications Incorporated	President
Colbert	Tyler	Emissol	
Masoudi	Mansour	Emissol	Director, R&D
Eppink	Jeffrey	Enegis, LLC	President
Biddle	Mike	Evok Innovations	Partner
Love	Darren	Evok Innovations	Associate
Whisenhunt	Donald	General Electric	Product Manager
Aveson	Steve	High Noon News	Journalist
Bragg-Sitton	Shannon	Idaho National Laboratory	Director, Integrated Energy & Storage Systems
King	Christine	Idaho National Laboratory	Director GAIN
Doughty	Brian	Individual	Consultant
Yoro	Kelvin	Lawrence Berkeley National Laboratory	
Kusuma	Julius	Meta / Facebook	Research Scientist
Brouwer	Ben	Montana Energy Office, Department of Environmental Quality	Energy Planning Section Supervisor
Patel	Babul	Nexant E&CA	Principal
Zoelle	Alex	Nexant E&CA	Energy Technology Team Lead
Wade	Jennifer	Northern Arizona University	Assistant Professor

Stakeholders (continued)

Last Name	First Name	Company Name	Job Title
Bradley	Gail	Northern Trust	Retired VP - Trust and Investments
Cortright	Randy	NREL	Senior Research Advisor
Dinh	Huyen	NREL	Scientist
Nawaz	Kashif	Oak Ridge National Lab	Group Leader
Pun	Betty	OGCI Climate Investments	Technology Principal
Neidl	Chris	OpenAir Collective	
Ferrer	Alberto	Power Renaissance	Team Leader
Zhu	Tianli	Raytheon Technologies Research Center	Sr Manager
Nicholas	Gary	SanTan Brewing Company	Operations Manager
Hunter	Chico	Salt River Project	Senior Engineer
Murdock	Tessa	Salt River Project	Research Engineer
Pelley	Don	Salt River Project	
Teni	Jennifer	Salt River Project	Engineer
Friedrich	Collin	Salt River Project—Phoenix	Engineer
Mendez	Alejandra	Salt River Project—Phoenix	Sr. engineer
Clark	Jason	SGI	Sr. Director Innovation & Sustainability
Klitzke	Joanna	Stripe Climate	Strategy & Ops
Shankar	Santhosh	Shell Energy	Strategy Advisor
Hait	Pam	Strategies	Principal
Page	Steve	SUN Behavioral Health	CEO
Gupta	Raghubir	Susteon Inc.	President

Stakeholders (continued)

Last Name	First Name	Company Name	Job Title
Jonza	Jim	3M Company	Corporate Scientist
Sauer	Cory	3M Company	Application Engineer
Skrelunas	Tony	Tribe-Awaken	
Deschene	Chris	Tosidoh, LLC	Principal
Gomes	K.	University of Pennsylvania	PhD Candidate
Logan	Kathryn	University of Arizona	Postdoctoral Research Fellow
Durcanska	Katka	UT Austin	Student
Durcanska	Katka	UT Austin	Student
Evanson	Ben	UT Austin	Student
Dell	Gina	W.L. Gore and Associates	Engineer
Scotti	Christine	W.L. Gore & Associates	Product Specialist

I-WEST Team Attendees

Last Name	First Name	Company Name	Job Title
Arcusa	Stephanie	Arizona State University	Postdoctoral researcher
Brandt	Bill	Arizona State University	Director of Strategic Integration, ASU LightWorks
Cirucci	John	Arizona State University	Chief Engineer
Dailey	Merritt	Arizona State University	Researcher
Flory	Justin	Arizona State University	Associate Director, Research; CNCE
Green	Matt	Arizona State University	Associate Professor
Hamblin	Lindsey	Arizona State University	PhD Student
Hanemann	Michael	Arizona State University	Professor
Javalkar	Vibhesh	Arizona State University	Research Associate
Lackner	Klaus	Arizona State University	Director, CNCE, ASU
Miller	Clark	Arizona State University	Professor
Nazari	Ani	Arizona State University	PhD student
Niimoto	Kacie	Arizona state university	grad research assistant
Page	Robert	Arizona State University	Project Manager
Patil	Sourabh	Arizona State University	Researcher
Schlosser	Peter	Arizona State University	VP and Vice Provost of Global Futures
Shokrollahzadeh	Hoda	Arizona state university	PhD student
Strangherlin barbosa	Thiago	Arizona state university	PhD Student researcher
Sriramprasad	Vishrudh	Arizona State University	CNCE Research Aide
Stechel	Ellen	Arizona State University	Co-Director of Lightworks and Professor of Practice

I-WEST Team Attendees (continued)

Last Name	First Name	Company Name	Job Title
Tamor	Mike	Arizona State University	Adjunct Professor/Technical Fellow (retired)
Atencio	Rachel	Los Alamos National Lab	Project Manager
Carey	James	Los Alamos National Lab	Research Scientist
Carter	Kelsey	Los Alamos National Lab	Postdoctoral researcher
Chillara	Vamshi	Los Alamos National Lab	Research Scientist
Fiorella	Richard	Los Alamos National Lab	Postdoc
Fox	Melissa	Los Alamos National Lab	Program Director
Gallegos	Crystal	Los Alamos National Lab	
Gattiker	Jim	Los Alamos National Lab	Scientist
Guthrie	George	Los Alamos National Lab	Dep Prog Dir
Heikoop	Jeffrey	Los Alamos National Lab	Group Leader
John	Kevin	Los Alamos National Lab	Chemistry Deputy Division Leader
Kress	Joel	Los Alamos National Lab	Deputy Division Leader
Maestas	Andrea	Los Alamos National Lab	Admin
Mehana	Mohamed	Los Alamos National Lab	Scientist
Neil	Chelsea	Los Alamos National Lab	Scientist
Pawar	Rajesh	Los Alamos National Lab	Scientist
Semelsberger	Troy	Los Alamos National Lab	Scientist
Van wijk	Jolante	Los Alamos National Lab	DGL
Thakkar	Harshul	Los Alamos National Lab	Postdoc Research Associate
Welch	Nathan	Los Alamos National Lab	Scientist

I-WEST Team Attendees (continued)

Last Name	First Name	Company Name	Job Title
Witkowski	Marc	Los Alamos National Lab	Business Development Executive
Spangler	Lee	Montana State University	Director, Energy Research Institute
Cunha	Luciane	Nat'l Energy Technology Lab	Supervisory Research/General Engineer
Fout	Timothy	Nat'l Energy Technology Lab	Research Engineer
Grant	Timothy	Nat'l Energy Technology Lab	
Lewis	Eric	Nat'l Energy Technology Lab	Research General Engineer
Matthews	Scott	Nat'l Energy Technology Lab	I-WEST Partner
Remson	Don	Nat'l Energy Technology Lab	general engineer
Vactor	Taylor	Nat'l Energy Technology Lab	I-WEST Partner
Vikara	Derek	Nat'l Energy Technology Lab	Subsurface Energy Analyst (Key Logic)
Shih	Js	Resources for the Future	Fellow
Fuller	Aaron	U.S. Department of Energy	General Engineer
Kim	Jai-woh	U.S. Department of Energy	Senior Program Manager
Litynski	John	US Department of Energy	DIRECTOR CARBON TRANSPORT AND STORAGE
Gerace	Selena	University of Wyoming	Research Scientist
Nye	Charles	University of Wyoming	Research Scientist
Phillips	Erin	University of Wyoming	Research Scientist

1.2 Workshop Agenda

January 19, 2021
8:00AM – 1:00PM MT

WebEx link to be emailed

8:00	Introduction, COP 26 & Direct Air Capture	**Peter Schlosser** Arizona State University
8:15	Welcome	**Matt Green** Arizona State University
8:30	Why DAC & I-WEST	**Jolante Van Wijk** Los Alamos National Laboratory
8:45	Q&A on DAC • Will DAC Work? When? • How much volume?	**Jolante Van Wijk** **Klaus Lackner** Arizona State University
9:30	CO_2 Panel Session *Focused on uses of captured CO_2* • Panel participants: Eric Dahlgren (Aircela), Derek Vikara (NETL), Raghubir Gupta (Susteon), Gary Nicholas (SanTan Brewing Company)	**Stephanie Arcusa** Arizona State University
10:15	Break	
10:30	Will Industry use DAC? *Select panel of companies who will or are considering the application of DAC technology* • Panel Participants: Julius Kusuma (Meta), Alex Dewar (Boston Consulting), Joanna Klitzke (Stripe), Chris Otte (CIBC)	**Bill Brandt** Arizona State University
11:15	Workforce and DAC *Jobs that the new energy transition will create in the Inner Mountain West* • Panel Participants: Tony Skrelunas (Tribe-Awaken), Algert Prifti (B&V)	**Jacob Moore** Arizona State University
12:00	Economics	**Michael Hanemann** University of California Berkeley
12:15	Policy: Next 15 years	**Peter Minor** Carbon180
12:30	Thank you and Close	**Matt Green**

1.3 Workshop Panel Questions

Dr. Klaus Lackner Q&A Discusion Topics:
Moderator: Jolante van Wijk (Los Alamos National Laboratory)

- How do you define DAC?
- What is the capacity and technology approach of currently operating facilities?
- Which DAC technology approaches are mature? Which may become mature in the next decade?
- What technology approaches look favorable / unfavorable in the I-WEST region?
- What drives the siting of DAC facilities in both technology-agnostic and technology-centric views? Can you commend on
    - infrastructure
    - economics
    - societal
    - environmental
    - disposal/use: energy resources, agriculture, fuels, etc
- What sites could be considered in the I-WEST region?
- Where do you see synergy of DAC with other aspects of the energy transition?
- What is a reasonable I-WEST employment scenario in the next 5 and 10-15 years, considering technical, scaling, infrastructure, political, environmental, social, and economic challenges?

Product Panel Discussion Topics:
Moderator: Stephanie Arcusa (Arizona State University)
Panelists: Eric Dahlgren (Aircela), Derek Vikara (NETL), Raghubir Gupta (Susteon), Gary Nicholas (SanTan Brewing Company)

- Can you introduce yourself and your company?
- Can you please explain your company's technology, what the product is, and what will the outcome be?
- What are your anticipated volumes and timings for the next 5-15 years?
- @ Eric: Who are your intended consumers?
- @ Gary: What are the benefits of installing CO2 capture technology in a brewery?
- @ Gary: How does the volume of the CO2 generated by fermentation compare to other uses?
- @ Gary: What is the potential for DAC in the brewing/ beverage industry?
- @ Raghubir: What infrastructure or regulation would your technologies need to scale and succeed?
- @ Derek: What geological sequestration is required for DAC?
- @ Derek: What types of sequestration are available in the I-WEST region, and of what capacity are they?
- @ Derek: What makes DAC a good candidate to pair with sequestration?

<u>Industry Panel Discussion Topics:</u>
Moderator: Bill Brandt (Arizona State University)
Panelists: Julius Kusuma (Meta), Alex Dewar (Boston Consulting), Joanna Klitzke (Stripe), Chris Otte (CIBC)

- Can you give some context around what your company does, and how it approaches DAC technology as a carbon management tool?
- @ Alex: Do we have enough momentum developing to meet the corporate goals or do we need something extra to push us?
- @Joanna: What do you see as the next step for Stripe after you've done the initial work?
- @Chris: What are your thoughts on what would be helpful to put the financing together?
- @Julius: How is Meta thinking about new collaborations that could address the points we've raised like aggregating demand and pulling the supply chain between capacity so that DAC systems can get off the ground?
- How are companies thinking about corporate positioning from a strategic point of view, not just now but in the next five years and beyond?

<u>Workforce Panel Discussion Topics:</u>
Moderator: Jacob Moore (Arizona State University)
Panelists: Tony Skrelunas (Tribe-Awaken), Algret Prifti (Black & Veatch), Chris Deschene (Tosidoh)

- @ Algert: What type of jobs does DAC provide and how will the job market grow over the next 5, 10, and 15 years?
- @ Algert: What are the benefits and drawbacks of the DAC jobs in terms of location, training levels, requirements, safety issues, etc.
- @ Tony: What are your thoughts around DAC and job opportunities and economic development in general and as it pertains to the tribes?
- @ Chris: What are your thoughts around DAC and job opportunities and economic development in general and as it pertains to the tribes?

A list of discussion prompts and questions from participants were compiled are provided in length in Appendix A – Participant Questions.

1.4 Summary of Key Takeaways from the Direct Air Capture Technical Workshop

Throughout the DAC Technical Workshop, participants were exposed to experts from across the industry including industry startups, national labs, university professors, and tribal energy experts. The diversity of backgrounds in this workshop allowed the discussion to inform a wide variety of topics and conversations. The peak number of participants in the workshop was recorded as 125, and the workshop closed at 12:45 with a participant count of 76. The information collected in this workshop will be critical to informing the I-WEST roadmap to carbon neutrality over the next 5, 10 and 15 years. For the panelists, this workshop offered the opportunity to engage with and hear from others who were working in similar areas of the DAC industry. The key takeaways from this workshop have been compiled and displayed below:

Context

- Acknowledge the world will overshoot the 1.5-2 °C limits and will need to reduce atmospheric concentrations by at least 70 ppm, likely more, to return to a “safer” condition. This will mean thousands of gigatons of sequestration over the coming century, more if fossil carbon use is not reigned in. This extra demand from new fossil fuel will most likely make negative emissions more expensive. Reframing carbon as a waste management problem, instead of simply a pollution problem, can offer more options. Carbon waste management as a service would require that all carbon emissions be sequestered, and the requirement would be more efficient to happen upstream, at the source.
- DAC can be defined as a technical means of getting carbon back from the environment which does not use photosynthesis as an intermediary.
- If DAC succeeds as an industry, it will be very large but likely not larger than the aviation industry, energy industry, or automobile industry. Land need for power generation, water usage considerate to local climatic conditions, potential emission of volatiles from sorbents, and sorbent waste disposal will all need to be addressed.
- DAC by itself does not constitute a solution for decarbonization nor for climate restoration, it is when combined with either carbon utilization or carbon sequestration that it becomes one. DAC for decarbonization includes products that substitute the use of fossil fuels, including liquid fuels and natural gas. DAC for climate restoration involves carbon sequestration, which can be temporary if liability for the carbon escaping is accepted but must ultimately be durable on timescales of tens of thousands of years.
- Quantification, verification, monitoring, and certification of the entire chain of activity is a pillar of the DAC industry that must be addressed. Certification of quantities and origin of raw materials (carbon from air, energy from renewables) as well as the intended use of the carbon (short lived products or sequestration) will need to follow yet-to-be established standards that expand and strengthen upon those currently existing.

Technology

- Mechanical DAC systems contact sorbents (solvents, amine-based solids) to CO_2 and remove the CO_2 from the sorbent using fans. Non-amine sorbents, material regeneration, and low temperature plasma CO_2 activation technologies are being developed. Passive DAC can be designed to run on intermittent power ensuring continued use without fossil energy. Passive DAC systems can work in a range of wind speeds but will struggle with vast variability. None of technologies are mature and it is too early to lock into one technology.

- Sorbents need to last a very long time (in terms of cycles, or years) to keep cost low. A priority is to develop more sorbents and to develop environmentally friendly large-scale waste disposal procedures for sorbents since every ton of CO_2 captured requires today approx. 1 kg of sorbent.
- DAC-to-fuel and Renewable Natural Gas, if produced using renewable energy, is one of several promising avenues to decarbonize the economy, particularly to substitute fossil fuels for transport, but also to store energy chemically economically over longer periods of time compared to batteries. Several companies are working on regeneration processes that can create liquid fuels or natural gas in one step instead of having through intermediary steps.
- Small, modular designs would provide flexibility, would be highly distributed, could attach themselves to existing infrastructure, and could be limited to consumers that do want the technology on their land or property. Small-scale DAC design also allows the bypassing of intermediate pilots and other scale-up risk that other larger scale designs will have to go through.
- The most promising storage formations are in saline bearing reservoirs. They are currently being used most prominently for enhanced oil recovery since the deployment of DAC for sequestration has been limited. An example of storage through mineralization can been in Project Orca in Iceland by Climeworks. Even in Orca, sequestration is happening at a relatively small scale.
- DAC has the advantage of not requiring transport for the captured CO_2 (a benefit in terms of infrastructure and logistics) and can be co-located with sequestration sites (saline water bearing reservoirs, mineralization in volcanic basalt formations) or directly with the consumers in the case of DAC-to-fuel. The challenge with locating DAC falls to finding a renewable reliable source of power near the end-use site.
- Artificial intelligence and machine learning can help accelerate calculations to discover more efficient technology or optimize performance.
- In the brewing and beverage industry, carbon re-capture from the fermentation process can be highly useful to smooth out the supply curves of smaller breweries because it reduces dependency on CO_2 shipments. Additionally, using the recaptured CO_2 reduces the capital expenditures.

Economics

- The biggest challenge for DAC is lowering cost from $500 today to under $100. There is currently no guarantee the industry can get there. However, most industries follow a cost-curve that reduces costs rapidly as total production numbers rise. The DAC industry will need to find out if it does so, too, by learning by doing and numbering up (mass producing) instead of scaling up. If one $50 million to $1B were spent subsidizing the improvement and scalability of DAC in an auction process, a clear determination could be made on whether this technology will follow other technologies on the learning curve or if it is an exception.
- CO_2 utilization in niche markets fetch high prices (e.g., $260-500/ton for the brewing industry) and production of CO_2 gas from DAC rather than fossil fuels directly by the consumer could reduce supply chain issues. Targeting niche CO_2 utilization could help lower cost in the short term. The cost of sequestration could be the tipping point for moving from majority-utilization market to a majority-sequestration market.
- First-movers can help bring down the cost of DAC by purchasing CO_2 or CO_2 reductions from promising companies. For example, the company Stripe purchased 1,600 tons from four DAC

companies at prices ranging from $300-2000/ton. Stripe also has customers who are asking them for participation opportunities.

- Carbon utilization and hydrogen are interconnected. For example, the production cost of Renewable Natural Gas depends on the value of hydrogen and depends on hydrogen programs.
- Along with policy, corporate decarbonization plans, net-zero pledges, science-based target setting, and a focus on carbon removal offsets as opposed to offsets of emission avoidance or reduction appear to be developing a market for DAC in various forms. DAC is seen as providing higher quality.
- DAC companies ought to develop viable business models, a plan to move to bankability as quickly as possible, engage with banks and advisors early, identify what the economics are for the project, and explore counterparties. Financing at scale may emerge through new CCUS projects. For now, DAC business models are in the early stages of maturity.

Policy

- New Power-to-gas programs and improved Low Carbon Fuel Standard from California would continue to incentivize DAC-to-fuel or Renewable Natural Gas technologies.
- 45Q is a good start but does not provide enough incentive and has a participation barrier that is too high, solutions to both are contemplated in the Build Back Better Act (increasing the $50/ton to ~$180/ton sequestered and decreasing or eliminating the minimum amount of CO_2 sequestered to qualify for the tax credit). Additionally, 45Q could be restructured to include sequestration through mineralization.
- Direct payment would remove some inefficiency in the financing through tax equity.
- Carbon Removal Leadership Act (CRLA) debated in New York aims to increase government procurement into high quality removal.
- Reducing friction for new players to get validation from accrediting companies would help development and deployment.
- An analysis of economic policies that promote the development of DAC ought to be centered between a top-down and bottom-up approach, looking at firms more like consumers, modelled to meet goals through change, and coordination and connection between actors.
- Policy will be a critical tool to enable DAC by supporting innovation, building capacity, reduce cost to a reasonable level through direct procurement, provide room for new ideas to be tested, and make sure the technology is accessible by anyone. Developing permitting for sequestration options beyond saline wells, like mineralization, would provide further incentives.
- Government regulation and standard setting for DAC would make the industry functional and safe. For example, by clarifying requirements for measurement and verification, and best practices for the industry.
- Government can also legislate supporting policies for DAC by buying materials to build low-carbon or carbon negative buildings, through buying CO_2 from DAC plants, or even building their own DAC plants.

Social considerations

- Tribes and rural communities have been and are continuing to be disproportionally impacted by climate change, the transition away from fossil fuels, and the activities producing the resources.

- Benefit of DAC extends from providing a pathway to a global net-zero that will positively impact communities affected by climate change to creating jobs in economically distressed communities or communities once reliant on the fossil fuel industry.
- The closer DAC can get to the end consumer, the more evident DAC technology will be as a viable tool to harvest carbon and make useful chemistries. This would enhance acceptability and awareness of the potential of DAC.
- DAC-related workforce will grow as DAC as a technology develops. In the next 5-10 years, science and engineering jobs will be needed to support research and development efforts, and deployment of demonstration units. As the technology develops, and deployment increases, traditional and specialty craft personnel will be required to manufacture, execute, build, operate the DAC plants. Supply chain, fabrication, and business-related jobs would also be expected to increase. DAC jobs are likely to be high-paying but also require diverse skills spanning across disciplines. Training for that will be necessary and to operate the DAC technology safely.
- Public benefits businesses provide a model for DAC business to maximize public good, create high paying jobs, and revenue that directly impact communities. Navajo Power is one such example, developed to support economics that would replace lost jobs and revenue from the fossil fuel industry shutdowns on Navajo Nation and beyond.
- Deal restructuring are needed to maximize benefits to Tribal Nations in exchange for land access. Ways of combining old and new industries ought to be devised (e.g., traditional farming combined with DAC-to-fuel), as are training and education certification programs. Developing capacity (ability to negotiate legally, access to technical training, business development, human power, educational capacity, and so on) and capital (infusion of resources) on Tribal Lands ought to be a pre-requisite.
- Entities working on the energy transition, including those focused on DAC, ought to be convened to produce a strategic plan that bridges across organizations and across to Tribal Nations. Tribal Nations are interested in learning about and utilizing DAC and want to be active owners and receive the maximum benefits of the technology.
- High-quality community engagement and cross-cultural communication has so far not been considered during past energy transitions and DAC can address some of these past mistakes. For example, by obtaining prior informed consent from communities for DAC projects.

Timing

- Move forward with the understanding that DAC is still a nascent technology, that is constantly changing, and should not be locked-in at this stage. In the short term, other technologies (like bio-based carbon capture and storage) will be more affordable and reliable, but in the medium-to-long term DAC with sequestration will take over because it does not have an upper limit in scale.
- Anticipated volumes and timing for small DAC-to-fuel systems within 5 years at production capabilities at megaton scale. Corporate actors are looking to be “bridge customers” to carry the market from the current price of DAC technology to the affordable future prices.
- Few sequestration projects are succeeding through the permitting process. The Infrastructure Bill provides support to ease backlogs and develop state-run programs.

Appendix A – Participant Questions

The following questions were asked by the participants of the workshop and used to facilitate discussion among the panelists and presenters. Answers are edited for brevity. Some questions were not answered live.

1. **Q&A with Dr. Klaus Lackner:**

   - We need to sequester CO2 to get to negative emissions. Making propane from CO2 would put it back into the atmosphere when it burns.
     - By making liquid fuels from atmospheric CO2, we are not adding new carbon to the atmosphere. We could continue to burn fossil fuels unabated and match every ton by sequestration, but this will mean massive amounts of sequestration especially if emissions continue to increase by 2% per year. On top of that, if we want to reduce atmospheric concentrations to a "safer" level, we are committed to 70-100 ppm reduction, which 100 ppm is 1500 Gt CO_2. As the cost of credible storage is unlikely to drop, this will further the need to disconnect from fossil fuels. And liquid fuels are desirable for transport so making them synthetically is worth it.
   - We have wind resource maps constructed to understand placement of turbines. Should we be using those maps to value the wind resource for DAC? Is there a limiting useful wind speed?
     - Passive DAC is limited by high variability of wind speeds. The machine would have to be designed for either low winds or high winds, but not both. The lower limit is very low, but if the wind is too slow, CO_2 uptake will be limited. Very high winds could topple the machine. Passive DAC does not gain from higher wind speeds because the CO_2 content is constant.
   - How is the local environment impacted around large scale DAC farms?
     - A DAC farm is smaller than a wind farm or a solar farm. Each unit is more compact than a windmill.
   - What is the water footprint of DAC technologies?
     - The footprint can vary. DAC with moisture swing solvents consume 10 tonnes of water per tonne of CO_2. If this water comes from desalinated ocean water, this will amount to \$5/tonne CO_2. Other DAC systems, like that of Climeworks, can produce water, even if expensive water. DAC technology can be on the spectrum of using a lot of water to producing water. The technology can be adjusted to be specific to the climatic conditions of a region.
   - Is there a ballpark number for how much CO2 can be removed by one pass through a DAC system (per unit volume of air passing through)?
     - This would be the wrong question to ask for passive DAC. For active DAC, because investment was made into run the machine, there is incentive in getting the most CO_2 out of the air. Active DAC attempts to collect 50-80% of the CO_2. For passive DAC, this is not a good figure because the airflow was free. The faster the air blows, the less efficient passive DAC would be. The amount of CO2 collected per kg, increases slowly, and becomes asymptomatic at some level. Passive DAC aims to collect 10-30% of the CO2

instead. The question that matters for passive DAC is how much was collected, and what was the uptake rate of the sorbent?

- Can you comment on the concept of community DAC? The idea of integrating DAC into the public sphere. On rooftops, in vehicles, and so on.
    - DAC in communities is important because it fosters acceptance. One plausible example would be a DAC unit in a remote location to replace propane tanks with DME tanks. Energy would then be stored for summer to winter. Other proposed examples of DAC on vehicles are not techno-economic or logistically feasible.
- Won't it always be cheaper to just offset emissions by sequestration, rather than conversion in fuels?
    - Future markets will have to figure it out. From an economic perspective, using fuels in the transportation sector in the distributed sector will require DAC. It is unclear at which price point sequestration will happen. It will depend on how supply and demand come together. In the short term, extra demand from fossil fuels will make the negative emissions more expensive because they will have to compete for the same resources. From a policy perspective, some of the resources necessary for sequestration ought to be protected from new fossil fuel use. For example, the policy could be to require that if one tonne of new fossil carbon comes out of the ground, two tonnes would need to be sequestered. The answer to this question will not so much depend on the cost of DAC, but rather the cost of solar electricity, versus the cost of hydrogen, versus the cost of sequestration on the other side.
- What might be the best mix of scaling up DAC technology to avoid 1.5C warming (360GT total beginning in 2020)? Which technologies are ready to scale up now and which will need to be delayed? What would be the best way to plan to scale up the different technologies?
    - The best bet from a cost perspective is bio-based, but these will never get large enough to solve the problem. However, they can start at an affordable price. Both bio-based and DAC will be necessary. DAC technologies need to be helped to get cheaper and meanwhile carbon needs to be stored in biomass. However, as one approaches 10 Gt CO2/year, the footprint of bio-based sequestration is huge. One can start with bio-based sequestration, but as times moves on, other technologies without limits on scale better be available and affordable.
- Will $50/ton 45Q incentive be enough to drive this?
- What do you think of the EDF Llissa O.'s focus on methane reduction now to avoid 1.5C?

2. Product focused Panel:

- What purity level of CO2 is needed prior to conversion to fuels?
    - It depends. Water is fine, especially if to end produce is methanol where water is produced anyway. In Aircela's case, the CO_2 is free of pollutants like sulfur. Oxygen is unwanted for obvious reasons.
- What is the footprint (size) of the 3 Tonnes Per Annum Aircela system?

- The entire device occupies a volume of roughly a cubic meter. The air collector occupies a volume of roughly a quarter cubic meter and the synthesis part and the storage of liquid fuels occupy another half cubic meter.

- How does the volume of CO_2 generated by fermentation compare to your other uses?
  - The volume of CO_2 generated from fermentation overshadows other uses. Over the past month, SanTan Brewing's CO_2 generation from fermentation has averaged 6000 kg/week. The CO_2 purchases are averaging 2300 kg/week for all uses over the same period, so generation is more than double the usage. The generation rate scales with volume (fermentation is fermentation), but the usage rate can improve as the process become more efficient. SanTan Brewing currently captures about 5.5kg/hour under ideal conditions, so the recovery system would have to grow substantially to make a dent in total CO_2 generation, but very real cost savings potentials are realized when usage efficiency increases.
- For sequestration in volcanic formations / basalt: Is dissolving CO_2 in water prior to subsurface injection a requirement?
  - CarbFix have found CO_2 dissolution in water is extremely advantageous in basalts in Iceland. Pilot projects supported by NETL in offshore basalts were planning a similar approach. Dissolving CO_2 in water could be favorable from an injectivity standpoint and help maybe slow or impede the mineralization process so injection can continue for longer. For larger scale CO_2 storage operations in saline, CO_2 is not mixed with water for several reasons related to capacity, corrosion and so on. More tests in basalts would determine if dissolution is indeed the best practice for that particular formation type.

3. **Industry focused Panel:**
   - How does corporate buyers of credits look at DAC vs. CCS from a point source for net-zero commitments?
   - Can you comment on the opportunities in small scale consumption? We heard this morning that the price of CO_2 for a brewery in Phoenix just changed from $260/tonne to more than $500/tonne. Even the old cost is quite steep.
   - How are offsets valued? For example, forestation is at $2/ton but the least helpful in avoiding 1.5C warming. How are more expensive and effective technologies valued and educated on?
   - What are the thoughts on needing a range of 1Gt to 40GT removal by 2032? What model(s) is this panel using?
4. **Workforce focused Panel:**
5. **Economics of DAC Presentation:**
   - Will the concept of waste management be addressed?
     - The concept of carbon pollution as waste management started at Resources For The Future in the 1960's. It is a powerful perspective. As the economics of pollution developed, it became more narrowly focused but the notion of carbon pollution as waste management is the relevant one for climate change. It is not just "there's a

regulation or the government has an effluent tax, what should I do?" Framing this problem as a waste management problem is a broader, more nuanced view that says, "I am doing something which is creating problems, it is creating waste, I have to clean up my own waste, how do I do that". That's a more profound problem and a broader view than others or regulation than "I have to pay a charge".

- Are there any technological analogies for the economics of DAC?
- Is there any other event in history that poses a crisis similar to the urgency of global warming and scaling up technology to avoid catastrophic consequences?

6. **Federal Policy around DAC Presentation:**

- Is there any new legislative effort to differentiate a negative carbon emission from a carbon avoidance emission in these 45Q credits?
    - No. Point source capture is an example of avoided emission. The way 45Q is set up, it only considers putting CO_2 underground so sectors like CCS qualify. Competing incentives are at play. The larger goal should be to make sure 45Q is as permissive and open to DAC as possible.
- Is there an effort to broaden the definition of carbon sequestration to mineralized storage - both above and below ground rather than in a Class 6 well?
    - Yes. There are political questions about how to get it done because some companies who are doing well with how they utilize 45Q, specifically fossil fuel companies, are likely to be concerned about changes and will be resistant. There is no question there won't be only one pathway for how carbon removal is done. DAC to saline aquifers will certainly be a big one but there will be others. The way 45Q is crafted today leaves open questions about how mineralization would even apply or if it could at all. How 45Q will change and on what time frame are open questions.
- Do you have any ideas of what additional new DAC policy will be in the potential Build Back Better Act?
    - In Build Back Better, the value of 45Q would increase and the threshold would be removed, and these two changes will be transformational. The big question for everyone is who buys DAC and how do we build a market for DAC. Driving down the cost will go a long way to answering those questions. There is also room for more R&D. We will certainly need better technology to get to the cost numbers and scale needed for a really robust direct air capture economy. The government is well placed to provide R&D dollars to try find what those new technologies could look like.
- If DAC is the bottleneck, would it make sense to subsidize it in applications like food grade CO_2 that do not result in sequestration? It would, after all, drive the cost down.
    - The plan for many companies is to find whatever applications that can, that are willing to pay higher dollar numbers, for the CO_2 because finding some utilization pathway is ideal to get paid and solve the cost problem. Eventually this is not a long term solution, because the calculation of how much carbon would be needed to replace some existing industries that are propped up by

fossil fuel, like chemicals, plastics, and textiles, even if all those were replaced with carbon from the air, there would still be excess CO_2 to remove and do something with. Utilization doesn't cover the whole scope of removals that will be needed so most of it will need to be sequestered. The right policies and incentives to enable that need to be figured out.

- How much of the new legislation will require the DOE or other agencies to act so that implementation is possible?
- What is the range of DAC that Carbon 180 is looking at? Metal Organic Frames, active DAC, passive DAC, BECUS, biostimulants on farms, etc.