Department of Energy Agreement: No. DE-FE0031952

Direct Air Capture Using Novel Structured Adsorbents

2022 Carbon Management Project Review Meeting

PI: Deborah Jelen, Electricore

Speaker: Dr. Adelaide Calbry-Muzyka, Climeworks

August 16, 2022

Project Overview
Cooperative Agreement No.: DE-FE0031959

- Award Period: 10/1/2020 through 09/30/2023
- Project Funding
  - Total Funding: $4,632,784
  - Federal Funding: $3,098,582
  - Cost Share Funding: $1,534,202 (33.12%)
- Project Participants
  - Prime: Electricore, Inc.
  - Design and Operation: Climeworks AG (Kiewit contracted as a vendor)
  - Technology: Svante, Inc.
  - Host Site: Kiewit
  - Cost Share Contributor: Southern California Gas Company
- DOE-NETL Team
  - Project Manager: Mr. Zachary Roberts
  - Contracting Officer: Ms. Angela Harshman
  - Award Administrator: Ms. Carla Winaught

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Svante

climeworks

Kiewit

SoCalGas
A Sempra Energy utility

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Objectives

The objective of this project is to advance direct air capture (DAC) technology through a novel combination of a vacuum-temperature swing CO_2 adsorption process and structured adsorbent beds (SABs). The project will validate current state of the art DAC systems and sorbent materials and provide the U.S. Department of Energy (DOE) and industry a benchmark for capability and cost effectiveness. The information will be beneficial for initiating production scale projects and directing following R&D.

The team will design, build and operate a 30 kilogram per day (kg/day) integrated field test unit capable of producing a concentrated CO_2 stream of at least 95% purity at a facility California.

Using applied research and development, the team will optimize the process design by reducing pressure drop and improving heat recovery.

Project Schedule & Success Criteria

Budget Period 1:

- 10/1/20 – 5/31/22
- Planning, Sorbent Selection, Engineering, Construction, and Commissioning

Budget Period 2:

- 6/1/22 – 9/30/23
- Integrated DAC System (IDS) Field Testing, Gen3 Sorbent Bed Development, and Technology Assessment

Decision Point	Basis for Decision/Success Criteria
Completion of Task 4	Successful completion of all work proposed in Tasks 2-4
	Submission of IDS process flow design package
	Completion of HAZOP study review
	Submission of host site letter of agreement confirming acceptance of the IDS design and HAZOP findings as well as construction and operation permission
Completion of Budget Period 1	Successful completion of all work proposed in Budget Period 1
	Submission of a Technology Maturation Plan
	Submission of Test Plan
	Manufacture of Gen2 SABs sized for the IDS field unit and characterization of KPIs listed in Table 1 of the SOPO (Appendix A).
	Submission of final IDS PFD with all equipment and piping layout shown and dimensioned
	Completion of equipment and sorbent procurement
	Completion of final assembly of the IDS including SABs
	Construction, Installation, and Commissioning Complete.
Completion of Project	Successful completion of all work proposed
	Completion of IDS field testing for 12 months with results showing KPIs as listed for Table 2 of the SOPO (Appendix A).
	Manufacture of Gen3 SABs sized for the IDS field unit consistent with KPIs as listed for Table 2 of the SOPO (Appendix A).
	Submission of (1) an updated State-Point Data Table; (2) Prescreening Techno-Economic Analysis; (3) Prescreening Life Cycle Analysis (<10% LCA inefficiency); and (4) an Environmental Health & Safety Risk Assessment based on the results of IDS field testing. TEA shows pathway to achieve DAC capture costs of \$100/tonne of CO_2 with 95% CO_2 purity.
	Submission of a Final Report

Project Background

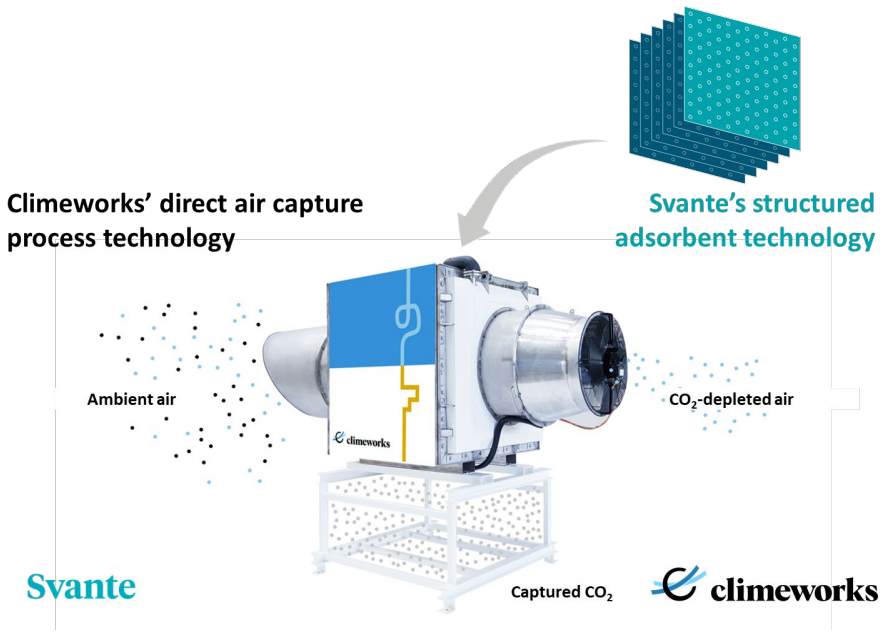
- Climeworks' Direct Air Capture (DAC) plant utilizes a vacuum-temperature swing adsorption process to filter the air and capture atmospheric CO_2. Air is drawn into the plant with fans and CO_2 within the air is chemically bound to Svante's novel solid structure sorbent material as the filter. One aspect of achieving low-cost DAC is to optimize energy use in this process. Supporting data confirms that TRL 4 was achieved by Climeworks DAC and Svante novel solid structure sorbent operation at the Climeworks laboratory.

- The proposed project is highly feasible. Materials, process, and system are developed and tested to TRL 4. Climeworks and Svante are leaders in their field with expertise and resources to conduct the work who have successfully collaborated earlier.

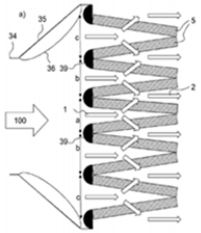
- The project will advance the technology to TRL 5 and result in a robust TEA on the DAC application.

- The field test will highlight gaps in performance that may benefit from further effort.

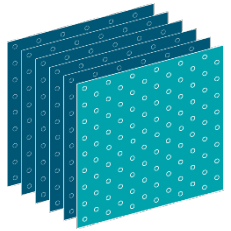
Motivation: Laminate beds for DAC



climeworks



Svante

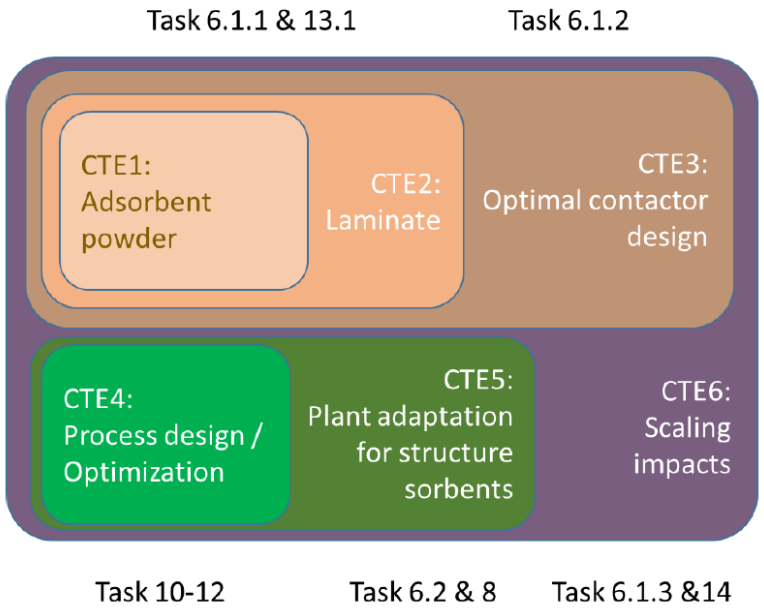


Climeworks structured packed beds	Svante laminates
+ modular, flexible hardware to optimize process parameters for many different sorbents in DAC	+ modular, adaptable laminate geometry can be adapted to various processes
+ equilibrium capacity > 1 mmol/g	+ equilibrium capacity > 1 mmol/g
- longer cycles than in structured sorbents	**+ fast cycles via fast mass transfer**
+ parasitic thermal mass low	**+ thermal mass ~as packed beds, lower than other structures (e.g. monoliths)**
+ low cost sorbents	**?** Cost vs packed beds when using fast cycling (to validate in project)
+ DAC performance known	+ flue gas performance known **?** DAC process conditions & life testing (to validate in project)

Development Approach

**Combined optimization of sorbent, structure, process –
all demonstrated in field for parametric variation and life testing.**

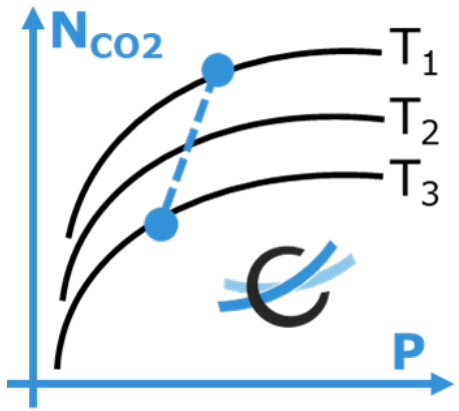
Sorbent & bed optimization

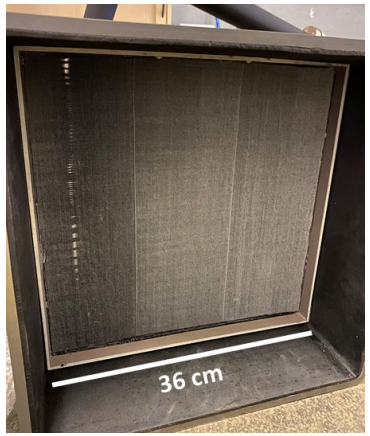


Integrated DAC System (IDS) field testing

Phase 1:
Parametric testing for process optimization

Phase 2:
Life testing



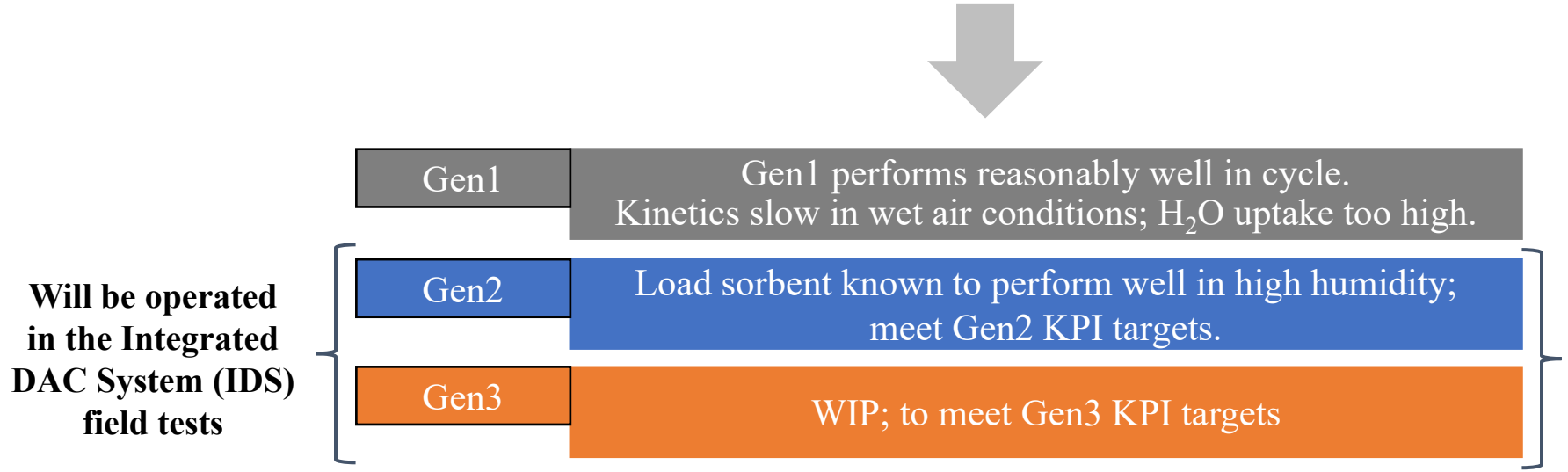


Progress and Current Status of Project: Sorbent and Bed Optimization

Three Generation Sorbent Bed Approach

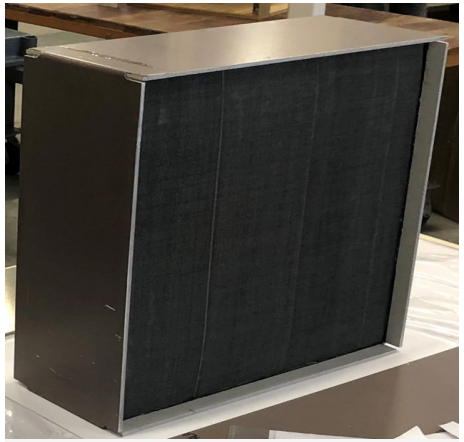
GOAL:

Improve kinetics in DAC (sorbent selection)
&
optimize bed geometry for DAC (higher spacer manufacturing)

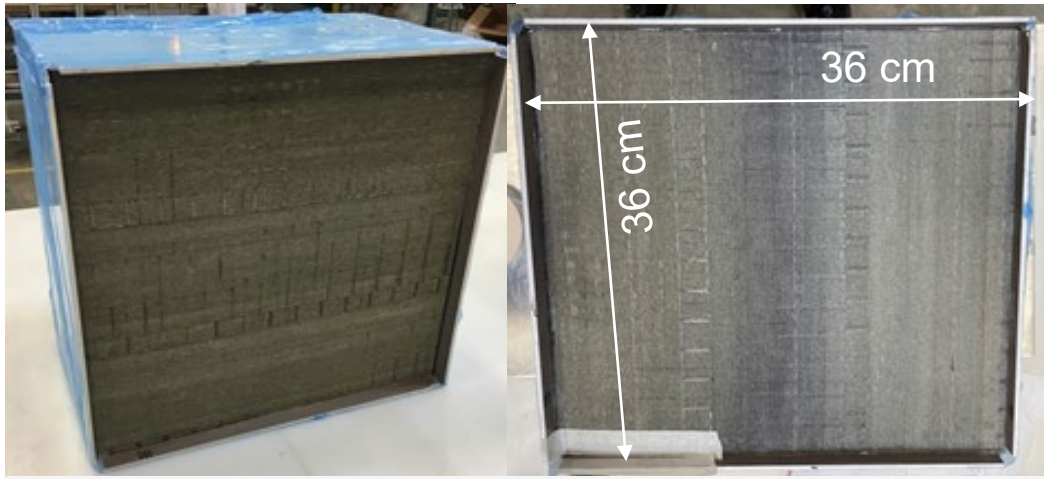


Will be operated in the Integrated DAC System (IDS) field tests

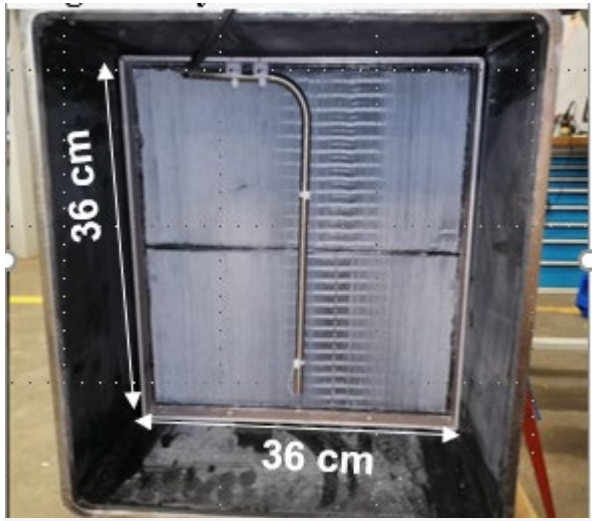
Gen1 & Gen2 IDS-scale Tests in Zurich to Measure Performance



IDS-sized Gen1 bed
Gen1 sorbent
(flue-gas optimized)
with flue-gas optimized
geometry



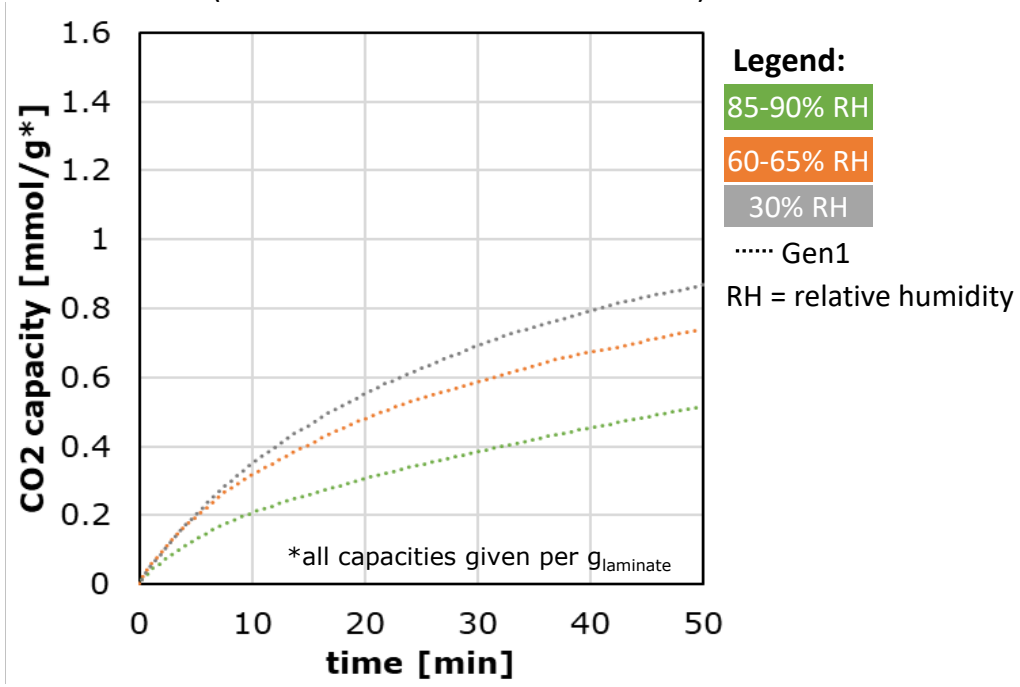
1st IDS-sized Gen2 bed (Q3 2021)
Gen2 sorbent (DAC-optimized)
with flue-gas optimized geometry



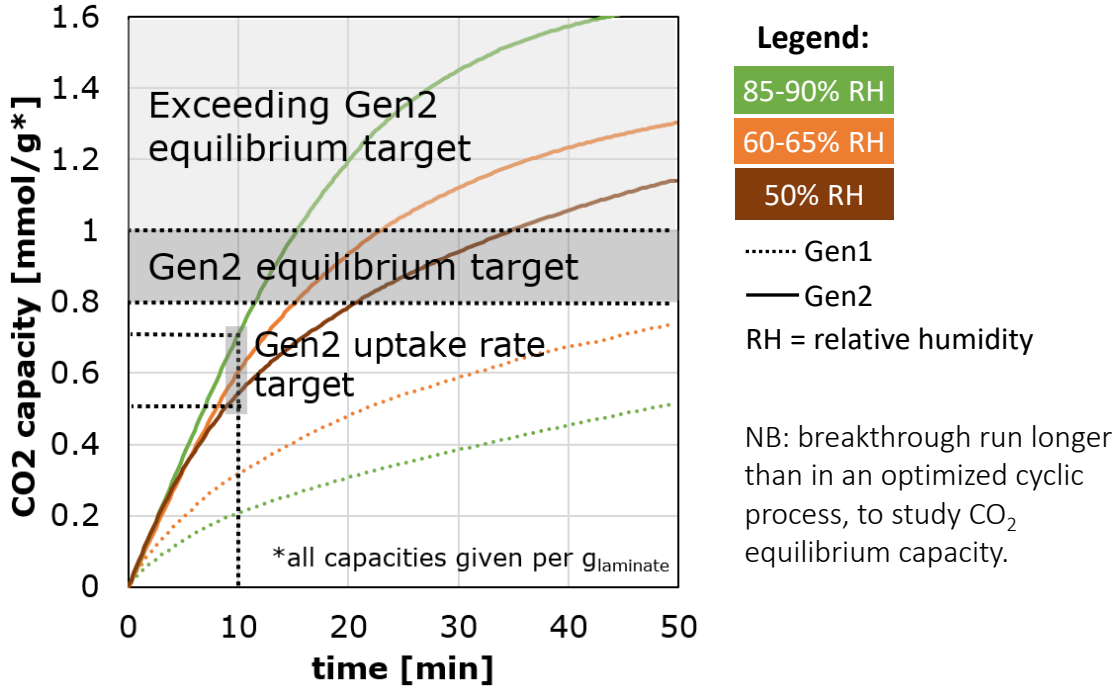
2nd IDS-sized Gen2 bed (Q4 2021)
Gen2 sorbent (DAC-optimized)
with DAC-optimized geometry

Performance in Climeworks DAC process at IDS scale

Gen1 (Svante structure + Svante sorbent)



Gen2 (Svante structure + Climeworks sorbent)



NB: breakthrough run longer than in an optimized cyclic process, to study CO_2 equilibrium capacity.

Adsorption results Gen1:

- ✓ >1000 cycles completed
- ✓ chemically steam-stable;
- ✓ good performance at low relative humidity (RH).
- ✗ good performance at high RH → **improve in Gen2**

	Gen 2 Performance Targets	*BP2 Target*	
✓✓	Equilibrium cyclic capacity [mol-CO_2/kg-laminate]	0.8-1	At adsorption >>20 mins
✓	Fast cycling CO_2 capacity [mol-CO_2/kg-laminate]	0.5-0.7	At adsorption = 10 mins
	Uptake rate [mol-CO_2/kg-laminate/min]	0.05-0.07	

Significant improvement of performance of Gen2 over Gen1 in high RH air, meeting or exceeding Gen2 targets.

Manufacturing taller spacers for DAC-optimized beds

	Gen1 bed & G2MPACK1 spacers	G2MPACK2 spacers	G3MPack
Printer type	Rotary spacer printing	Linear Spacer printing	Linear Spacer printing
Material	Resin	Ceramic	Ceramic
Shape	Dome	Cylinder	Cylinder
Surface	Curved	Flat	Flat
Height increase c.f. flue gas optimal spacers	N/A	1.5x-2x	2x-3x
Progress	N/A	Medium-spacer height & improved alignment	High spacer height & more uniform
Photos of laminate			

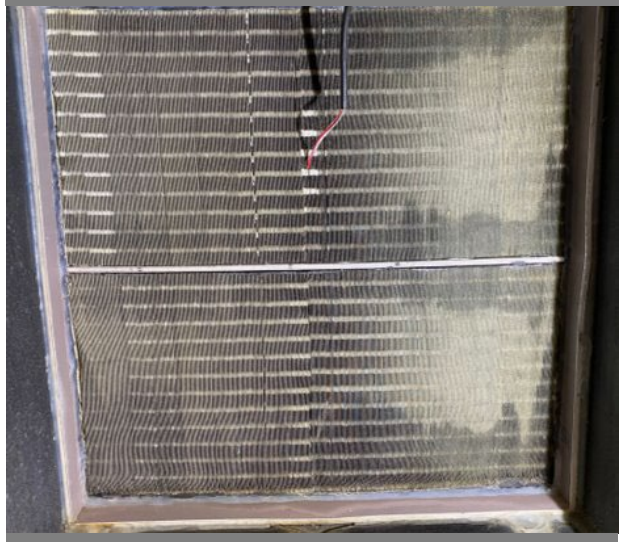
Gen2: Completed Mechanical Tests in Zurich

No signs of mechanical failure observed after >4500 cycles

Steam inlet / air outlet, after 60 cycles

Steam inlet / air outlet, after 1512 cycles

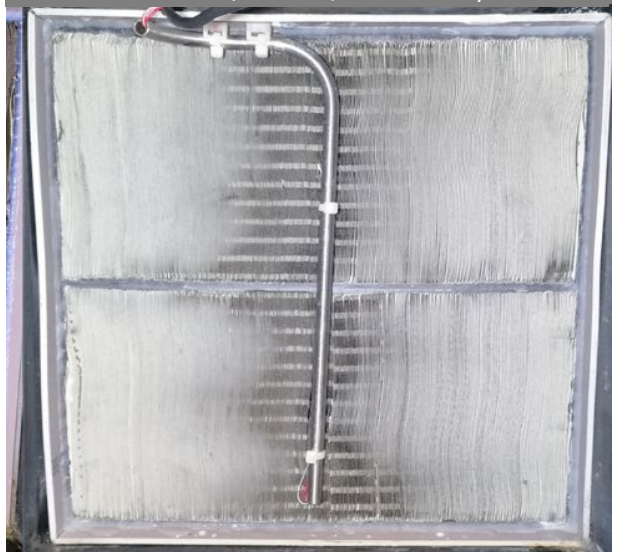
Steam inlet / air outlet, after 3534 cycles



Steam inlet / air outlet, after 4546 cycles

Steam outlet / air inlet, after 60 cycles

Steam outlet / air inlet, after 1512 cycles



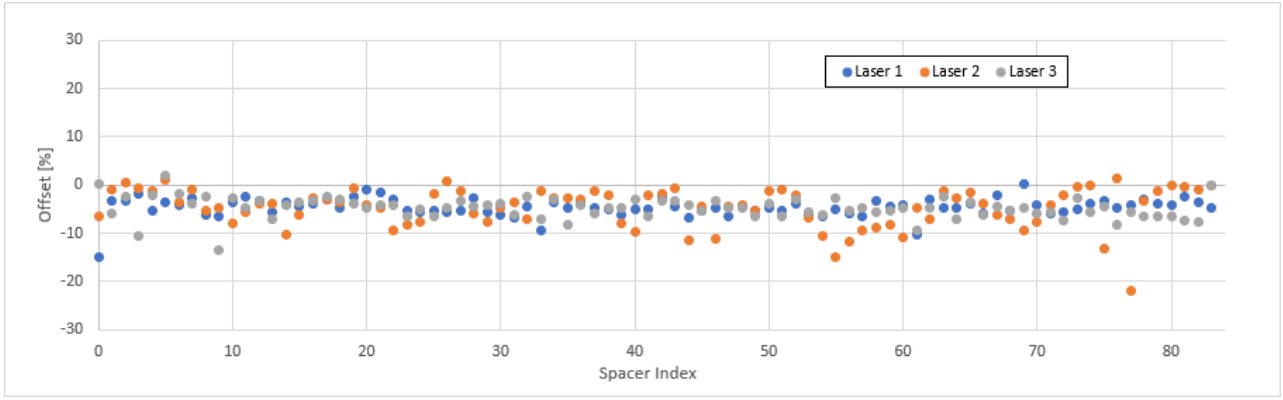
Steam outlet / air inlet, after 3534 cycles

Steam outlet / air inlet, after 4546 cycles

Manufacturing improvements continue to ensure scalability

Developing automated spacer height measurements

New spacer printing technology + laser measurement gives higher spacer height and narrower spacer height distributions



Gen2 beds with further optimized geometry are ready for field testing in California

Looking ahead to Gen3

Field Testing Targets

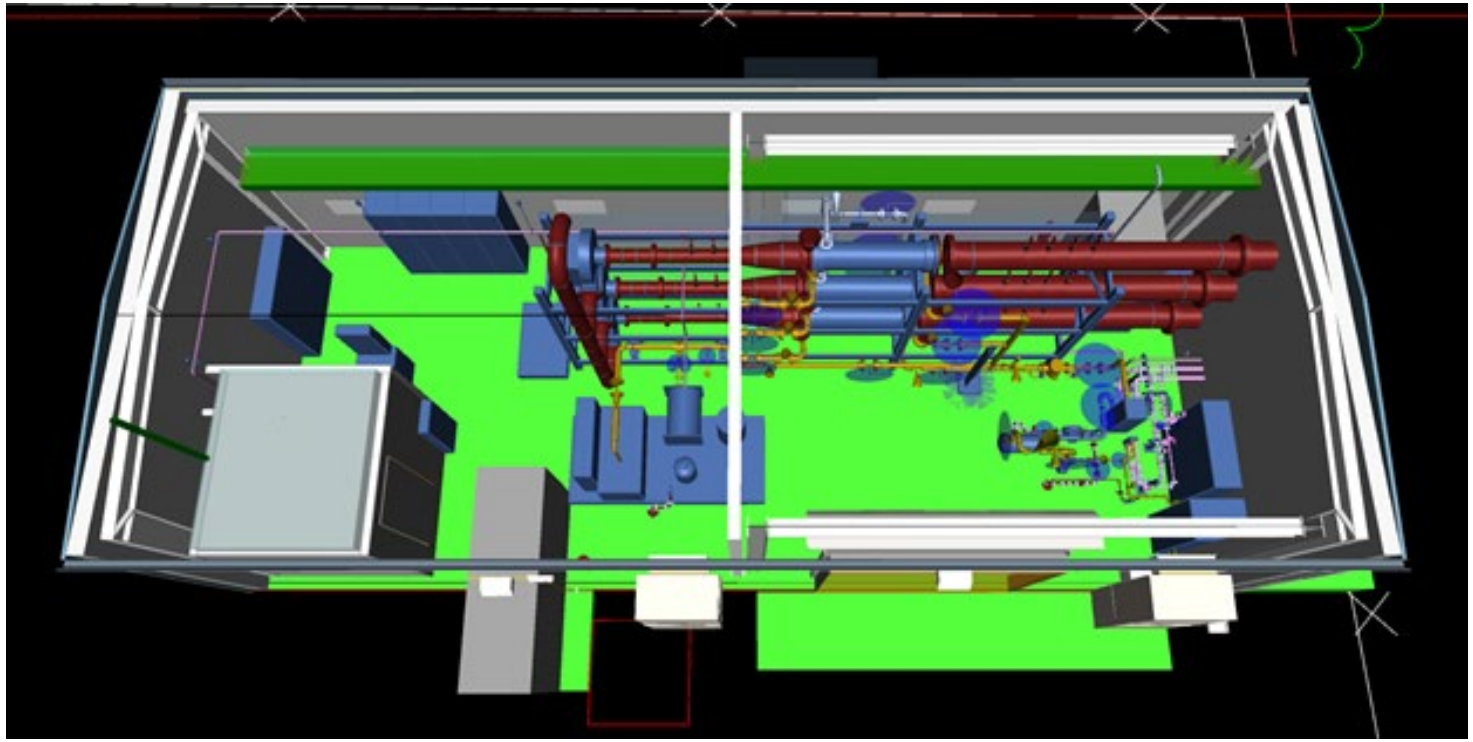
	BP2 Target [Gen 2]	*BP2 Target [Gen 3]*
Equilibrium cyclic capacity [mol-CO_2/kg-laminate]	0.8-1	1.1-1.6
Fast cycling CO_2 capacity [mol-CO_2/Kg-laminate]	0.5-0.7	0.8-1
Uptake rate [mol-CO_2/Kg-laminate/min]	0.05-0.07	0.08-0.1
Cyclic lifetime [% average capacity loss in ~1 year]	<10%	<5%
Pressure drop [Pa]	800-1000	400-700

Gen3 focus:

- Gen3 equilibrium capacity targets already met in Gen2.
- Further optimization:
  - Reduced pressure drop
    - Higher spacers; optimized spacer pattern
  - Improved lifetime
    - Process optimization for mechanical and chemical stability (e.g. steam flow uniformity, condensation management)
    - Lessons learned from current testing at Climeworks
  - Continue exploring other sorbents

Integrated DAC System(IDS) Field Testing: Construction, Installation and Commissioning

Integrated DAC System (IDS) test plant

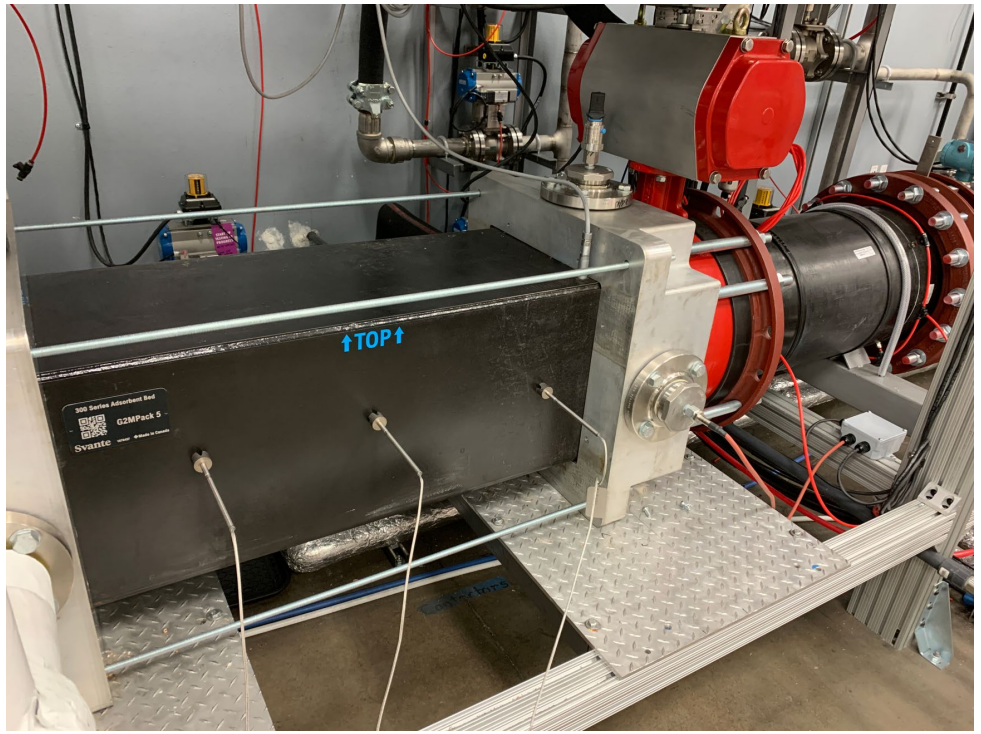


- At Kiewit site in Fountain Valley, CA
- 3 independent lines allow simultaneous process development and long-duration life testing
- Test plant (rather than production plant) to allow team to optimize and extract generalizable data
- Based on existing Zurich test plant, adapted for US utility standards

Construction: February 2022 (month 1)

Construction: July 2022 (month 6)

Svante laminate beds loaded:

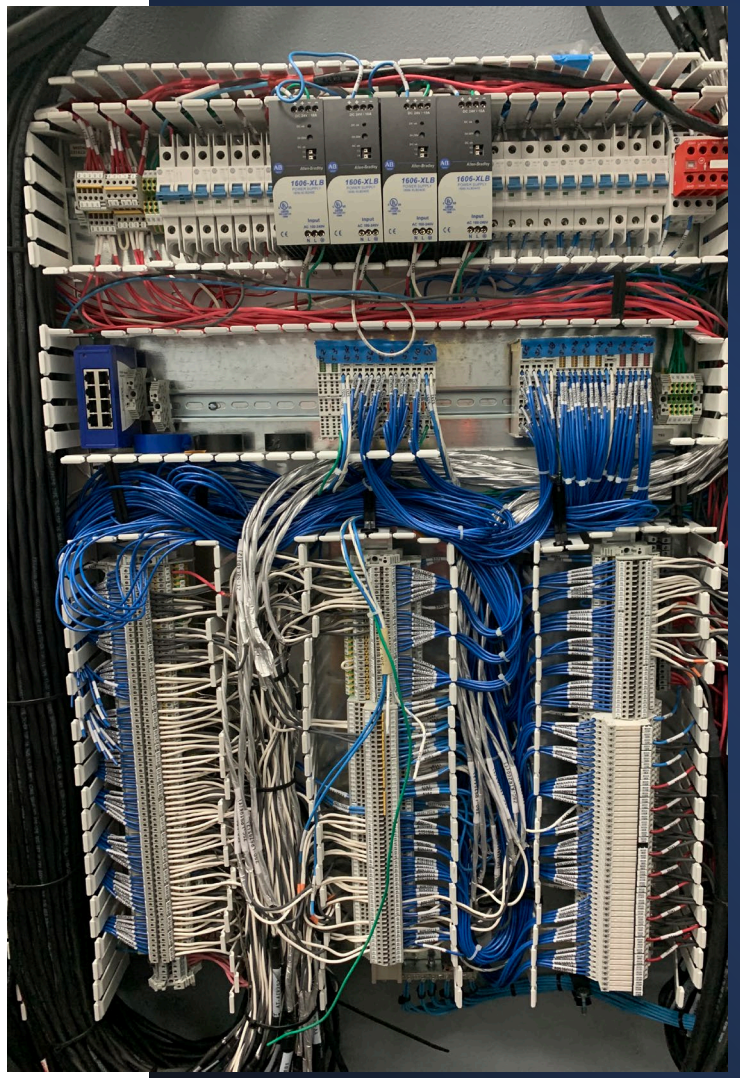


Commissioning

- Cold commissioning (May/June 2022)
  - Single components
  - Subsystems
  - Electrics

- Hot commissioning (July/August 2022)
- Last components integrated
- From subsystems to fully integrated system

- Site Acceptance Test (August 2022)



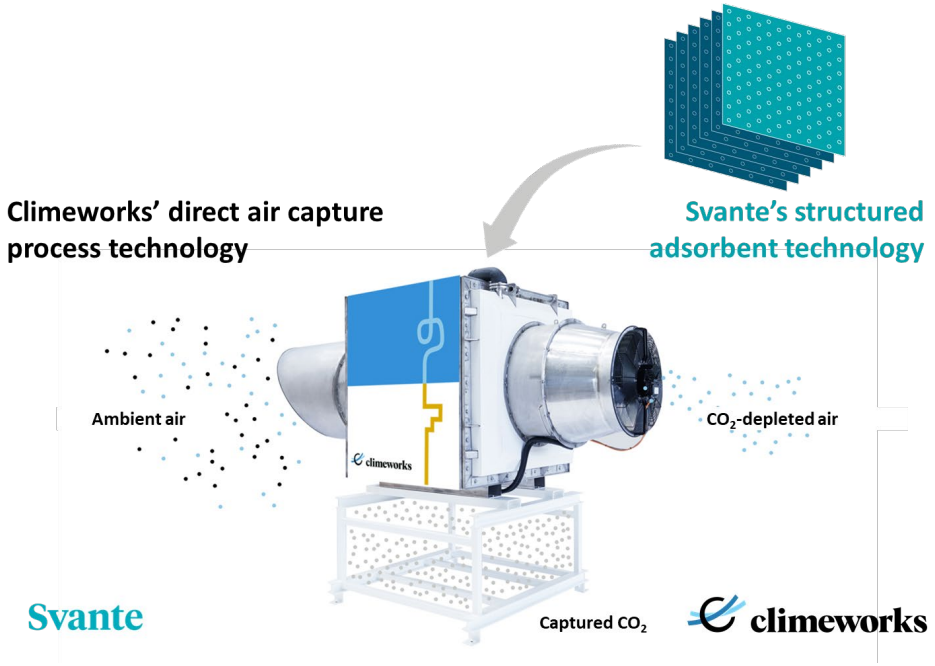
Next Steps

In this project: Reach TRL5

- Complete optimization of sorbent structure and process for DAC (→ Gen3)
- Demonstrate & study structured sorbent's lifetime (→ field testing) to estimate costs based on measured data (→ TEA) and evaluate key environmental impacts (→ LCA, EHS)

Beyond this project: TRL & MRL maturation

- Scale up sorbent structure to standard module size; number up collector units; scale up plant.



Project Progress

- **Demonstrating laminate beds in DAC**
- Sorbent & laminate bed developed for DAC in Gen1 and Gen2 iterations, by close collaboration between Svante and Climeworks
- Demonstrated Gen2 ambitious KPI targets in Climeworks DAC process in Zurich, and mechanically stability > 4500 cycles
- Gen2 laminate beds built and ready to test in IDS test plant
- IDS test plant in California is built and in final stages of commissioning

	Task / Subtask	Milestone Title & Description	Planned Completion Date
✓	1.1	Project Management Plan	12/31/2020
✓	1.2	Technology Maturation Plan	12/31/2020
✓	2	Preliminary Process Flow Design	11/30/2020
✓	3	HAZOP	11/30/2020
✓	4	Host Site Agreement	11/30/2020
✓	5	Test Plan	3/31/2021
✓	6	Gen 2 Sorbent Selection	4/1/2022
✓	6.1	Increased kinetics and CO_2 uptake at variable relative humidity	4/1/2022
✓	6.1.1	Laminate production (Gen1 and Gen2)	4/1/2022
✓	6.1.2	Optimized contactor geometry selection	4/1/2022
✓	6.1.3	Lifetime studies on small scale SAB samples	4/1/2022
✓	6.2.1	Sorbent Material Selection	12/31/2021
✓	6.2.2	New prototype enclosure	12/31/2021
✓	6.2.2.1	Spacer manufacturing process	12/31/2021
✓	6.2.3	Identify and develop low-cost substrates	12/31/2021
✓	7	Preliminary Technology EH&S Risk Assessment	3/31/2021
✓	8	IDS Process Flow Design	2/26/2021
✓	9.1	Long lead procurement	5/28/2021
✓	9.3	SAB production	3/1/2022
✓	10.1	Permitting	11/31/2022
✓	10.2	Site Preparation	3/3/2022
✓	10.3	Host site safety review	3/17/2022
✓	10.5	IDS assembly	4/29/2022
✓	10.6	SAB installation	5/24/2022
(✓)	11	Installation and Commission of IDS	5/31/2022
	12.1	Field Testing	5/31/2023
	12.2	Field Testing Data	7/28/2023
	13.2	Process Performance and Test Time	7/28/2023
	14.1	Technology EH&S Risk Assessment	09/29/2023
	14.2	Pre-screening Techno-Economic Analysis	09/29/2023
	14.3	Pre-screening Life Cycle Analysis	09/29/2023
	14.4	State-Point Data Table	09/29/2023

Thank You!

The team is thankful for the continued support of this project including:

- The Office of Fossil Energy and Carbon Management
- DOE NETL
- DOE Project Manager – Zachary Roberts
- DOE Technology Manager – Andrew Jones
- SoCalGas

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For more information contact:

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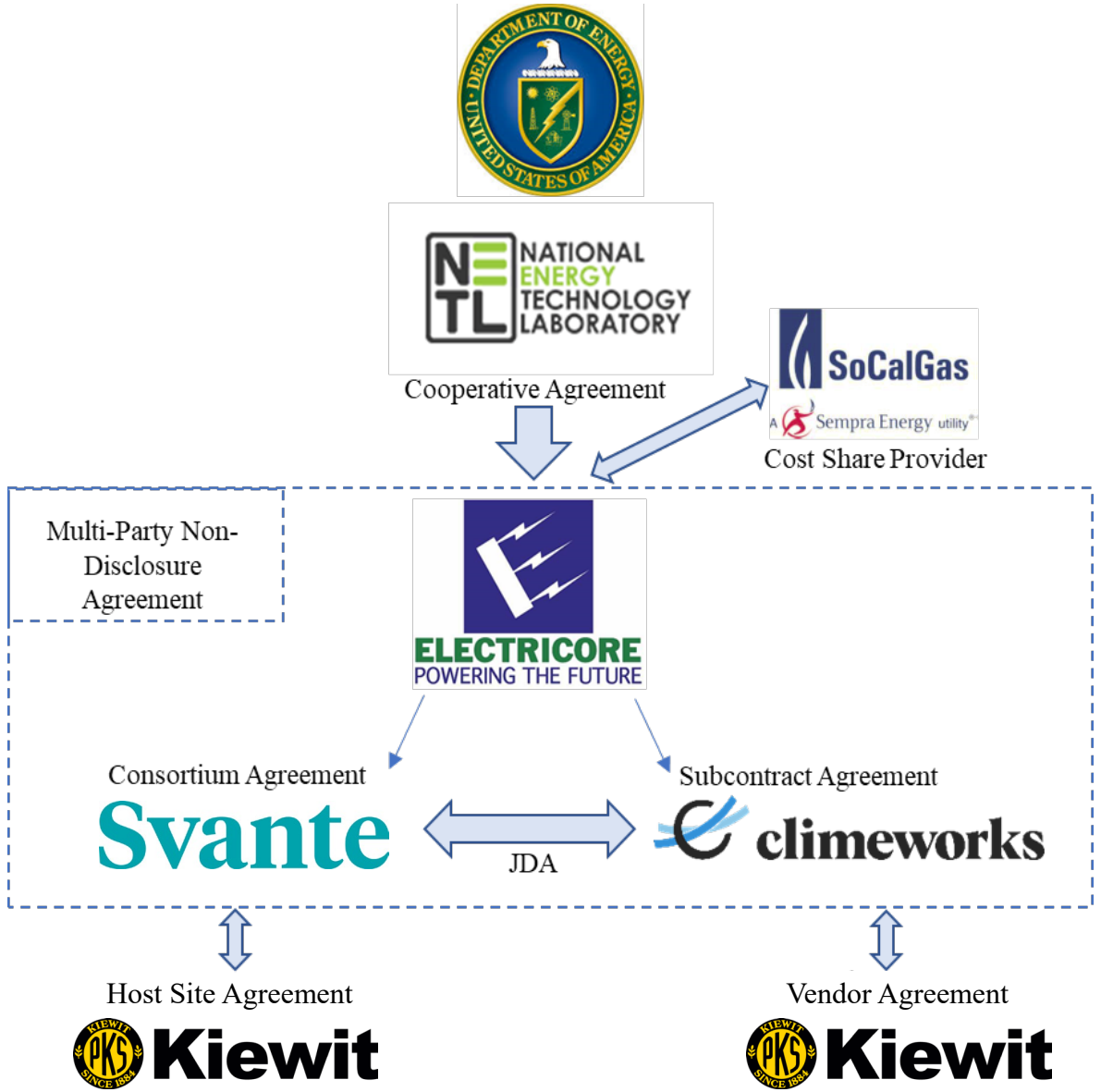
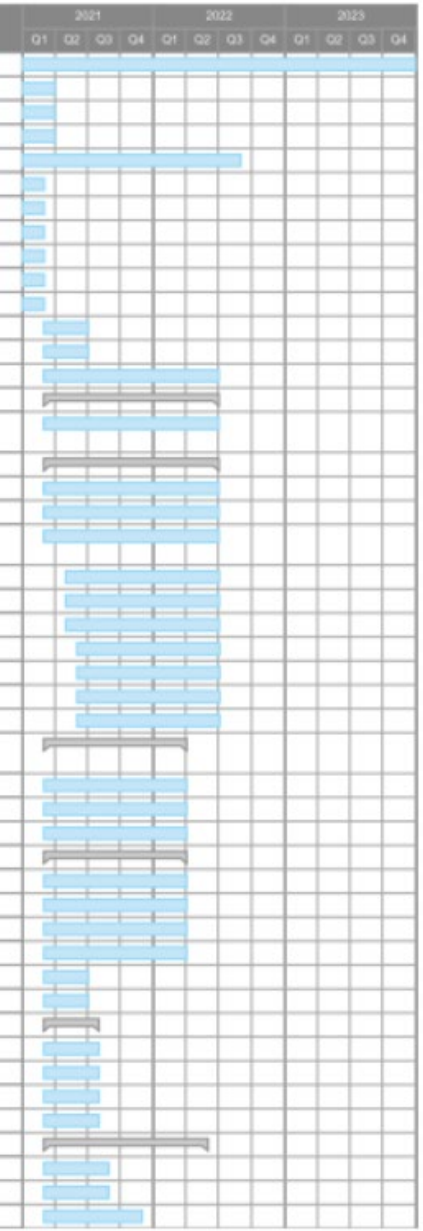
Appendix A: Organization Chart



Appendix B: Gannt Chart

Task Name	Start	Finish
PROJECT MANAGEMENT AND PLANNING	10/01/20	09/29/23
Task 1.0 - Project Management and Planning	10/01/20	12/31/20
Milestone – Project Management Plan	10/01/20	12/31/20
Milestone – Technology Maturation Plan	10/01/20	12/31/20
BUDGET PERIOD 1 - FIELD UNIT PLANNING AND DESIGN	10/01/20	05/31/22
Task 2.0 - Preliminary Process Flow Design	10/01/20	11/30/20
Milestone - Preliminary Process Flow Design	10/01/20	11/30/20
Task 3.0 - HAZOP	10/01/20	11/30/20
Milestone - HAZOP Report	10/01/20	11/30/20
Task 4.0 - Permit Planning	10/01/20	11/30/20
Milestone -Host Site Agreement	10/01/20	11/30/20
Task 5.0 - Prepare Test Plan	12/01/20	03/31/21
Milestone - Test Plan	12/01/20	03/31/21
Task 6.0 - Sorbent Optimization	12/01/20	04/01/22
Milestone - Gen 2 Sorbent Selection	12/01/20	04/01/22
Subtask 6.1 - Increase Kinetics and CO2 Uptake at Low and High Relative Humidity	12/01/20	04/01/22
Milestone - Increased Kinetics and CO2 Uptake at Relative Humidity	12/01/20	04/01/22
Subtask 6.1.1 - Developing Gen1 and Gen2 sorbents	12/01/20	04/01/22
Milestone - Laminate Production (Gen1 and Gen2)	12/01/20	04/01/22
Subtask 6.1.2 - Development of optimized contactor geometry for low pressure drop	12/01/20	04/01/22
Milestone - Optimized Contractor Geometry Selection	02/01/21	04/01/22
Subtask 6.1.3 – Lifetime studies	02/01/21	04/01/22
Milestone - Lifetime Studies on Small Scale SAB samples	02/01/21	04/01/22
Subtask 6.1.4 – Laminate production	03/01/21	04/01/22
Subtask 6.1.5 - New enclosure design	03/01/21	04/01/22
Subtask 6.1.6 - New spacer manufacturing process	03/01/21	04/01/22
Subtask 6.1.7 - Identification and development of low-cost	03/01/21	04/01/22
Subtask 6.2 - Sorbent Structure Manufacturing Optimization (Manufacturing Team	12/01/20	12/31/21
Subtask 6.2.1- Manufacture Gen1 and Gen2 Beds	12/01/20	12/31/21
Milestone - Sorbent Material Selection	12/01/20	12/31/21
Subtask 6.2.2 - Enclosure	12/01/20	12/31/21
Milestone - New Prototype Enclosure	12/01/20	12/31/21
Subtask 6.2.2.1 - Manufacturing of up to 1.5 mm spacer height	12/01/20	12/31/21
Milestone - Spacer Manufacturing Process	12/01/20	12/31/21
Subtask 6.2.3 – Develop New Substrate	12/01/20	12/31/21
Milestone - Identify and Develop Low-Cost Substrates	12/01/20	12/31/21
Task 7.0 - Preliminary Technology EH&S Risk Assessment	12/01/20	03/31/21
Milestone - Preliminary EH&S Report	12/01/20	03/31/21
Task 8.0 - Detailed Engineering	12/01/20	04/30/21
Subtask 8.1 - 3D model	12/01/20	04/30/21
Subtask 8.2 - Final PFD and P&IDs	12/01/20	04/30/21
Subtask 8.3 - Plot plan	12/01/20	04/30/21
Milestone - Final IDS Process Flow Design	12/01/20	04/30/21
Task 9.0 - Procurement	12/01/20	03/01/22
Subtask 9.1 - Long Lead Procurement	12/01/20	05/28/21
Milestone - Long Lead Procurement	12/01/20	05/28/21
Subtask 9.2 - Procurement and Vendor Specifications	12/01/20	08/27/21



Appendix B: Gannt Chart (cont)

Task Name	Start	Finish
Subtask 9.3 - Sorbent Procurement and Manufacturing	12/01/20	03/01/22
Milestone - SAB Production	12/01/20	03/01/22
Task 10.0 – Construction	01/10/21	05/24/22
Subtask 10.1 - Permitting	01/12/21	11/31/22
Milestone - Permitting	01/12/21	11/31/22
Subtask 10.2 - Site Preparation	12/06/21	03/03/22
Subtask 10.3 - Host Site Safety Review	03/03/22	03/17/22
Milestone - Host Site Safety Review	03/03/22	03/17/22
Subtask 10.4 - Subsystem Assembly	01/10/21	11/19/21
Subtask 10.5 - Final Assembly and On-Site Construction of IDS	01/04/22	04/29/22
Subtask 10.6 - Sorbent Bed Installation	01/05/22	05/24/22
Milestone - SAB Installation	01/05/22	05/24/22
Task 11.0 – Final Installation and Commissioning	04/01/22	05/31/22
Milestone - Installation and Commission of IDS	04/01/22	05/31/22
Subtask 11.1 – Testing and Commissioning of DAC System	04/01/22	05/31/22
Milestone – IDS Site Acceptance Test Protocol	04/01/22	05/31/22
BUDGET PERIOD 2 - INTEGRATED FIELD TESTING	06/01/22	09/29/23
Task 12.0 – Field Testing	06/01/22	09/29/23
Subtask 12.1 - IDS Testing at Host Site	06/01/22	05/31/23
Milestone – Field Testing	06/01/22	05/31/23
Subtask 12.2 - Data Collection and Analysis	06/01/22	07/28/23
Milestone – Field Testing Data	06/01/22	07/28/23
Subtask 12.3 - Autopsy and Full Characterization of Gen2 and Gen3	06/01/22	09/29/23
Subtask 12.4 - System Removal	06/01/23	09/29/23
Task 13.0 - Gen3 Sorbent Bed Development	06/01/22	07/28/23
Subtask 13.1 - Gen3 Characterization	06/01/22	06/01/23
Subtask 13.2 - Manufacture Gen3 Beds	06/29/23	07/28/23
Milestone – Process Performance and Test Time	06/29/23	07/28/23
Task 14.0 - Technology Assessment	06/01/23	09/29/23
Subtask 14.1 – Final Technology EH&S Risk Assessment	06/01/23	09/29/23
Milestone – Technology EH&S Risk Assessment	06/01/23	09/29/23
Subtask 14.2 - Pre-screening Techno-Economic Analysis (TEA)	06/01/23	09/29/23
Milestone – Pre-Screening Techno-Economic Analysis	06/01/23	09/29/23
Subtask 14.3 - Pre-screening Life Cycle Analysis (LCA)	06/01/23	09/29/23
Milestone – Pre-screening Life Cycle Analysis	06/01/23	09/29/23
Subtask 14.4 - State Point Data Table	06/01/23	09/29/23
Milestone – State Point Data Table	06/01/23	09/29/23