DIRECT AIR CAPTURE USING NOVEL STRUCTURED ADSORBENTS

DE-FE0031959

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U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management and Natural Gas & Oil Research Project Review Meeting

Virtual Meetings August 2 through August 31, 2021

Project Overview
Cooperative Agreement No.: DE-FE0031959

- **Award Period: 10/1/2020 through 09/30/2023**
- **Project Funding**
  - Total Funding: $3,714,202.00
  - Federal Funding: $2,500,000.00
  - Cost Share Funding: $1,214,202.00 (32%)
- **Project Participants**
  - Prime: Electricore, Inc.
  - Design and Operation: Climeworks AG (Kiewit contracted as a vendor)
  - Technology: Svante, Inc.
  - Host Site: Wintec Energy Ltd.
  - Cost Share Contributor: Southern California Gas Company
- **DOE-NETL Team**
  - Project Manager: Mr. Andrew Jones
  - Contracting Officer: Ms. Angela Harshman
  - Award Administrator: Ms. Carla Winaught

ELECTRICORE
POWERING THE FUTURE

Svante

climeworks

Wintec ENERGY LTD

SoCalGas
A Sempra Energy utility

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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 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.

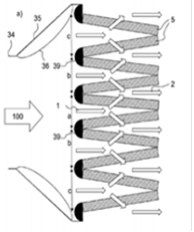
The proposed project is highly feasible. Materials, process, and system are developed and tested to TRL 4. Climeworks and Svante are leaders in their field with expertise and resources to conduct the work who have successfully collaborated earlier.

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

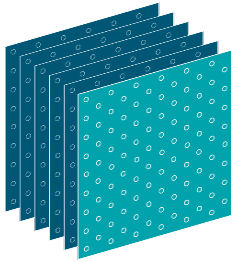
The field test will highlight gaps in performance that may benefit from further effort.

Motivation: DAC Sorbent Structures

climeworks



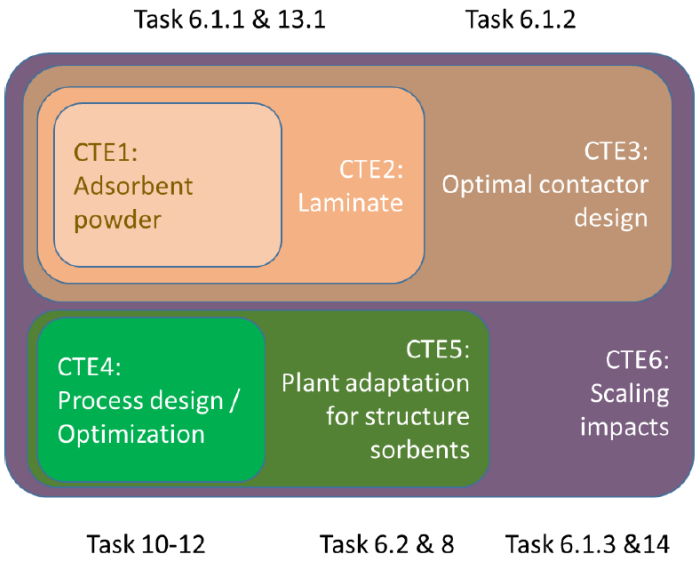
Svante



Climeworks structured packed beds	Ceramic Monoliths	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**	**+ fast cycles via fast mass transfer**
+ sorbent thermal mass < ceramic monoliths'	**- high parasitic thermal mass**	**+ thermal mass similar to packed beds**
+ low cost sorbents		**?** Cost vs packed beds when using fast cycling (to validate in project)
+ mechanically and chemically robust		+ robust in flue gas **?** DAC life testing (to validate in project)

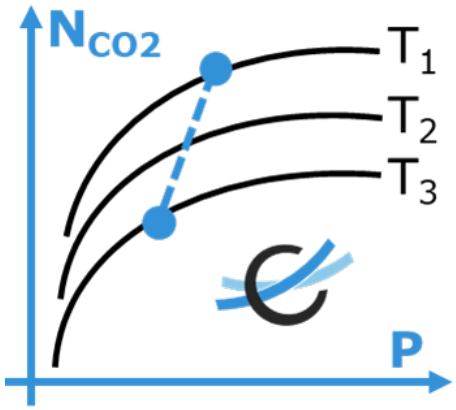
Development Approach

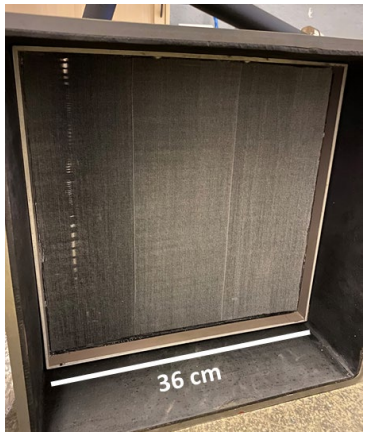
Combined optimization of sorbent, structure, process – all demonstrated in field for parametric variation and life testing.



From Technology Maturation Plan

Integrated DAC System (IDS) field testing	
Phase 1: Parametric testing for process optimization	Phase 2: Life testing

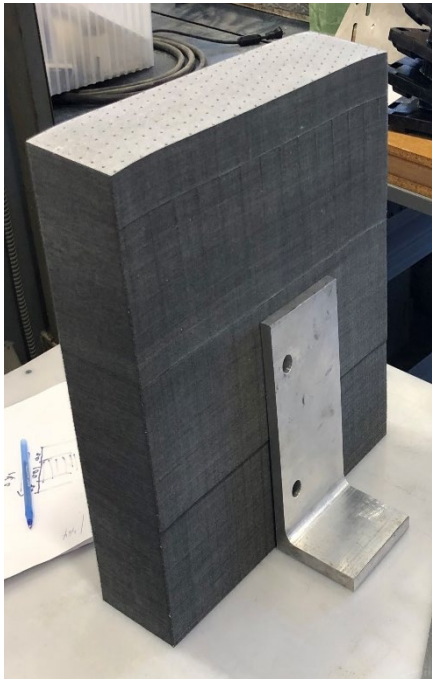




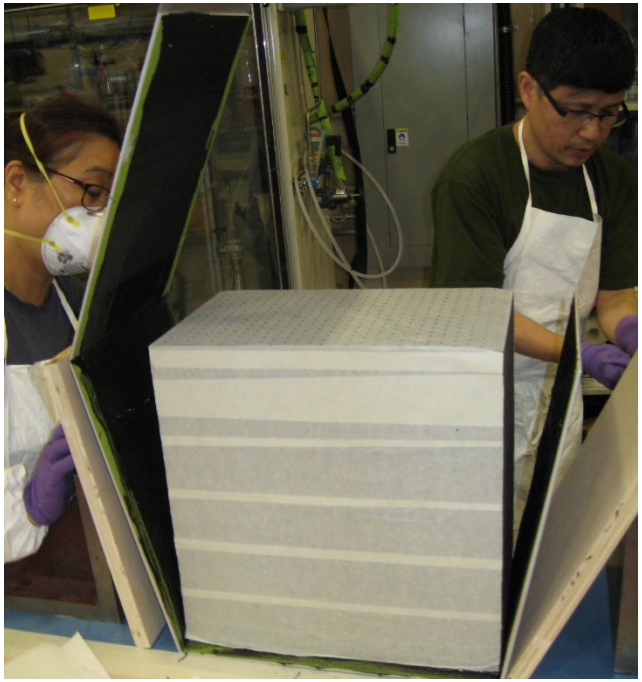
Gen1 (Svante structure + Svante sorbent)

Manufacturing

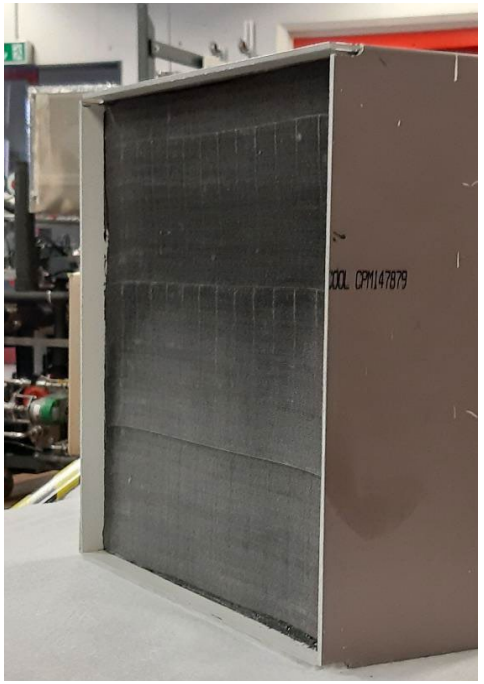
Laminate stack



Framing



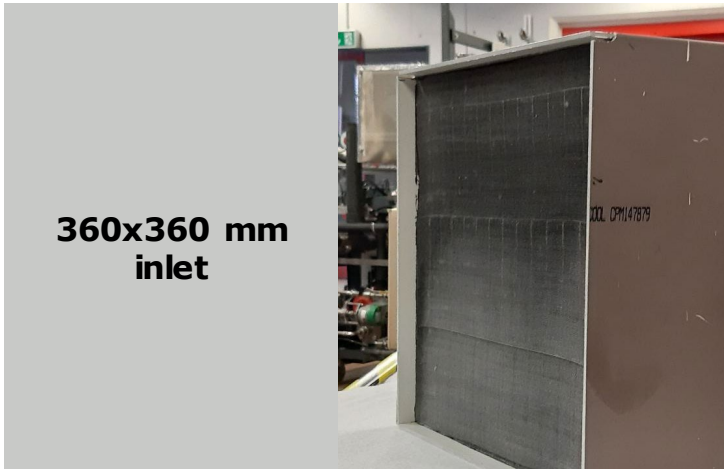
Bed



Gen1 is based on Svante structure geometry and one of Svante's sorbents (originally optimized for point-source capture)

Gen1 (Svante structure + Svante sorbent)

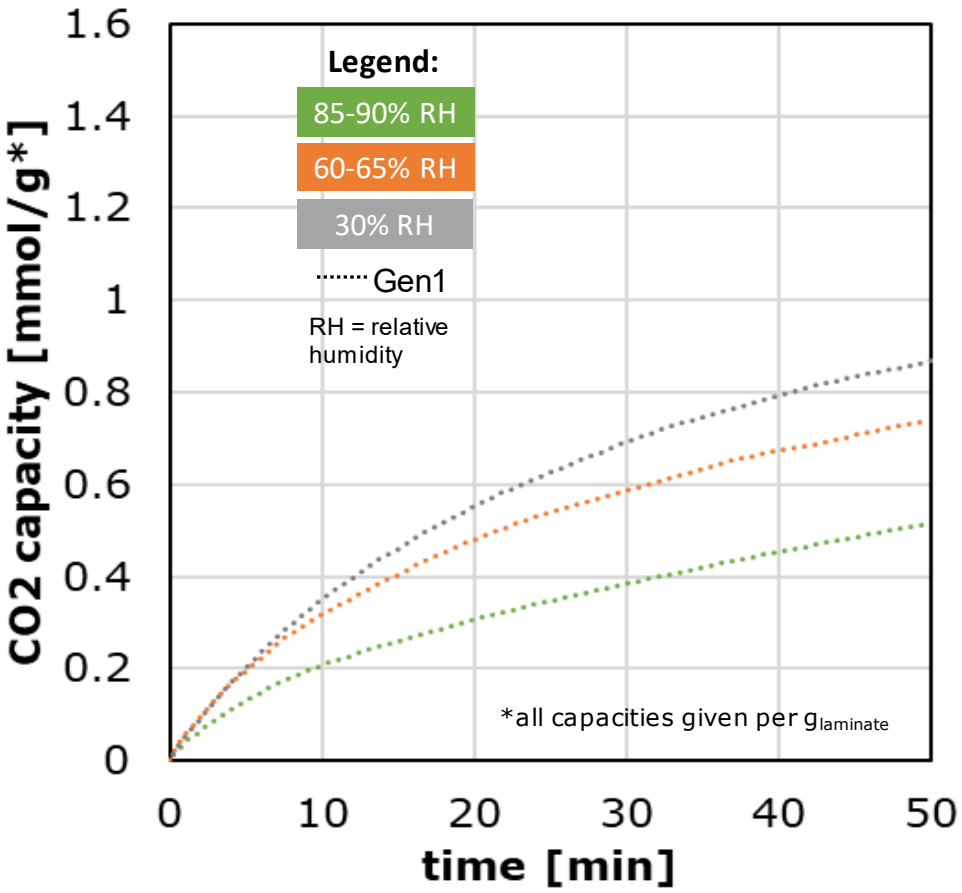
Performance in Climeworks DAC process



Adsorption results Gen1:

- ✓ >1000 cycles completed
- ✓ chemically steam-stable;
- ✓ good performance at low relative humidity (RH).
- × good performance at high RH

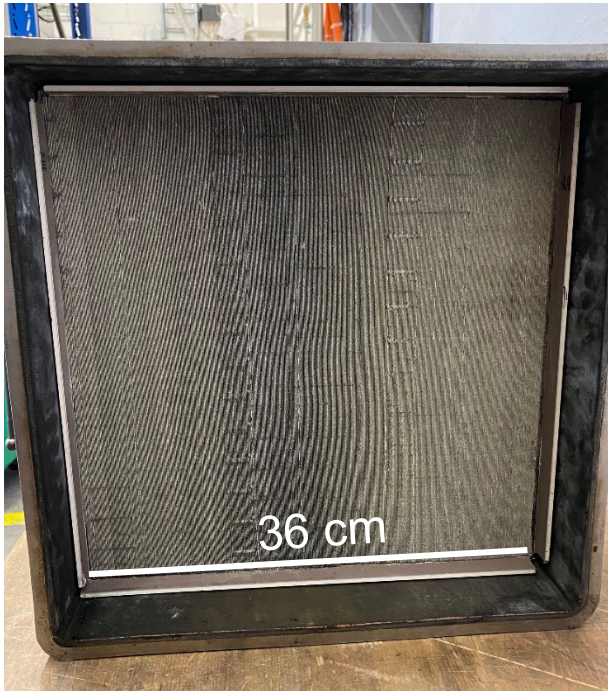
Goal of Gen2:
Improve performance at high RH



Gen2 (Svante structure + Climeworks sorbent)

Manufacturing

One of Climeworks' sorbents was efficiently transferred to the high surface, high kinetics Svante laminates, and IDS bed was manufactured using the same geometry of Gen1 bed.



Gen2 is based on Svante structure and one of Climeworks' sorbents (optimized for direct air capture)

Gen2 (Svante structure + Climeworks sorbent)

Performance in Climeworks DAC process

Performance Metrics	*BP2 Target [Gen 2]*
Equilibrium cyclic capacity [mol-CO_2/kg-laminate]	0.8-1
Fast cycling CO_2 capacity [mol-CO_2/kg-laminate]	0.5-0.7
Uptake rate [mol-CO_2/kg-laminate/min]	0.05-0.07

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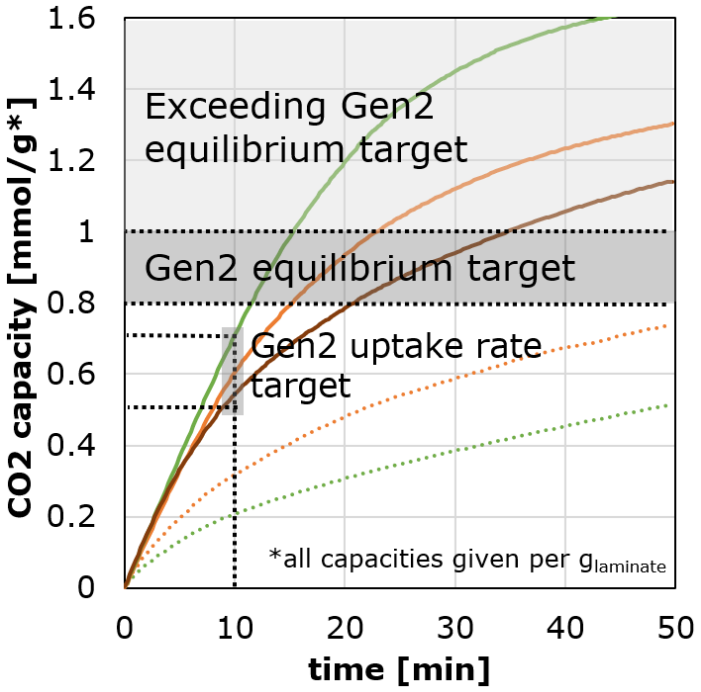
At 10 mins adsorption



Legend:

85-90% RH

60-65% RH

50% RH

Gen1

Gen2

RH = relative humidity

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

As targeted: Significant improvement of performance of Gen2 over Gen1 in high RH air.

Towards Low Pressure Drop:
Higher Spacer Development

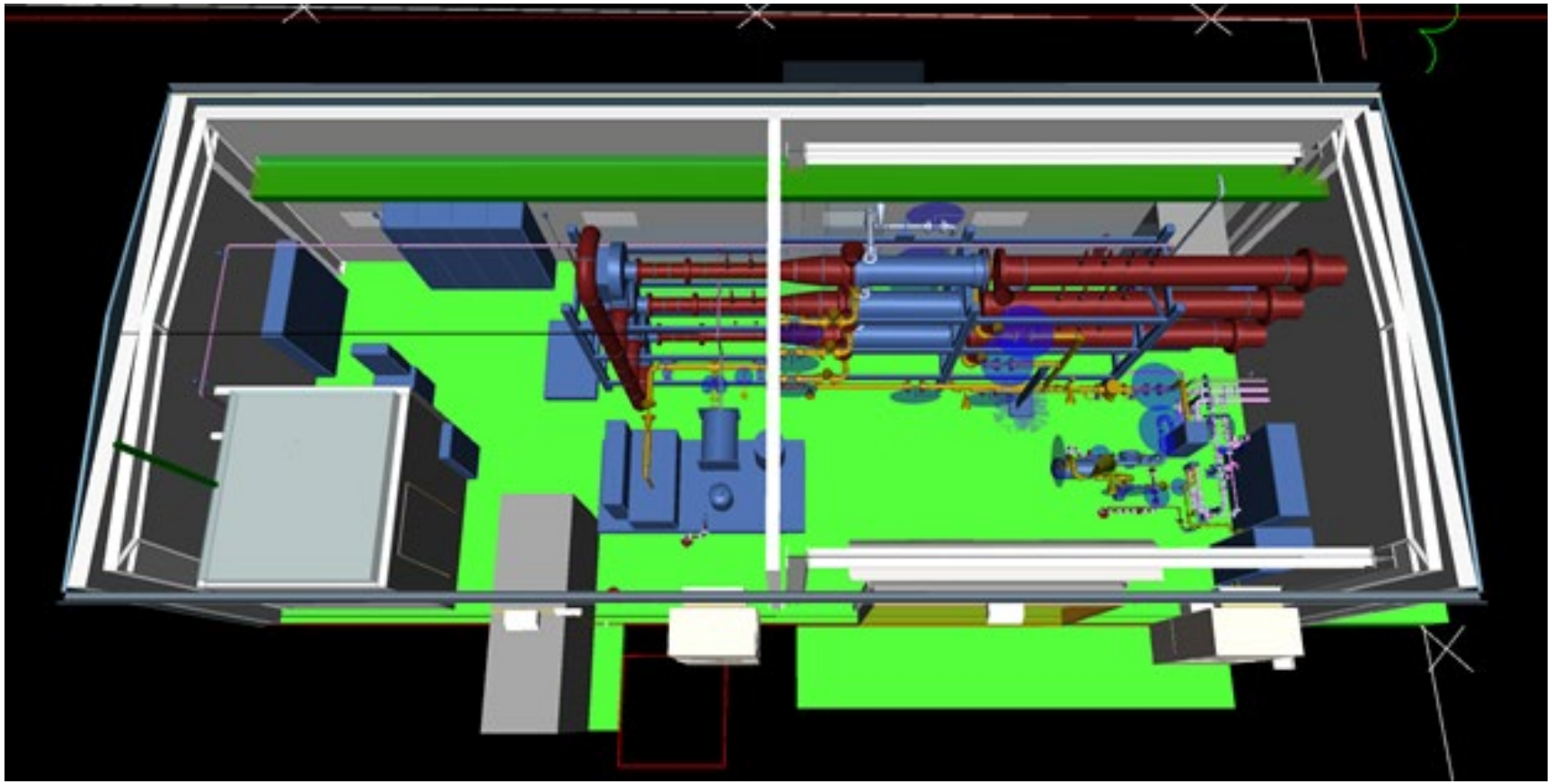
New Spacer (DAC)

1) Cylinder shape
2) Flat surface
3) Better alignment and stack rigidity for higher spacer height

Previous Spacer

1) Dome shape
2) Curved surface
3) Better for high speed manufacturing and lower spacer height

Integrated DAC System (IDS) test plant



Progress:

- Detailed engineering completed
- Long-lead item quotes received
- Based on existing Zurich test plant; adapted for US utility standards

Project Milestones

	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

Success Criteria

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

Next steps

In this project and beyond:

- Complete optimization of sorbent structure and process for DAC
- Demonstrate & study structured sorbent's lifetime to estimate costs based on measured data
- Scale up sorbent structure to standard module size; number up collector units; scale up plant.

Development Summary

Structured sorbent-process optimization

☑ Gen1	Gen1 performs reasonably well in cycle. Kinetics slow in wet air conditions; H_2O uptake too high.
☑ Gen2	Load sorbent known to perform well in high RH; meet Gen2 targets. *Next:* decrease pressure drop
☐ Gen3	Improve lifetime

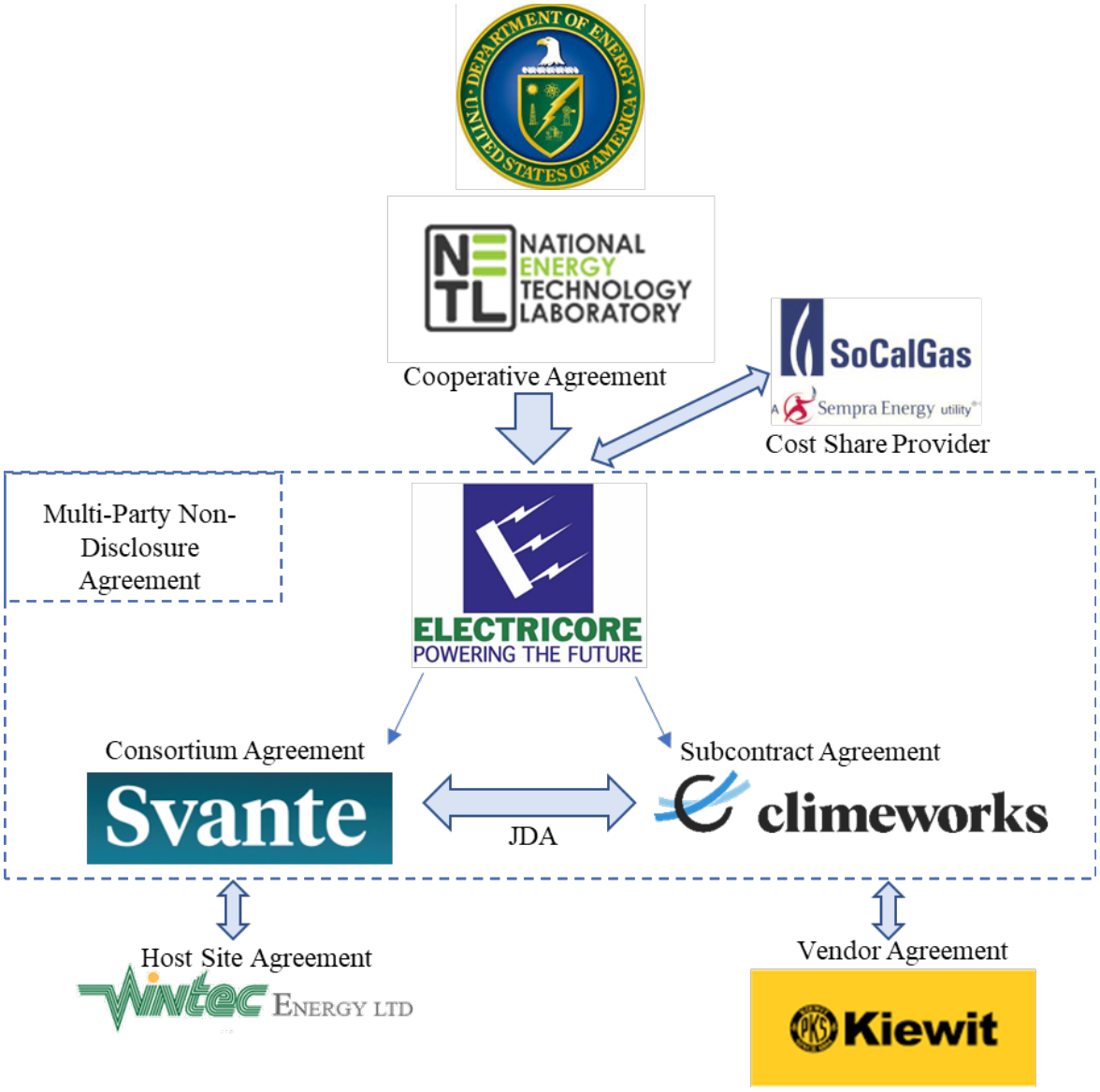
Field testing unit

☑	Detailed engineering completed on schedule

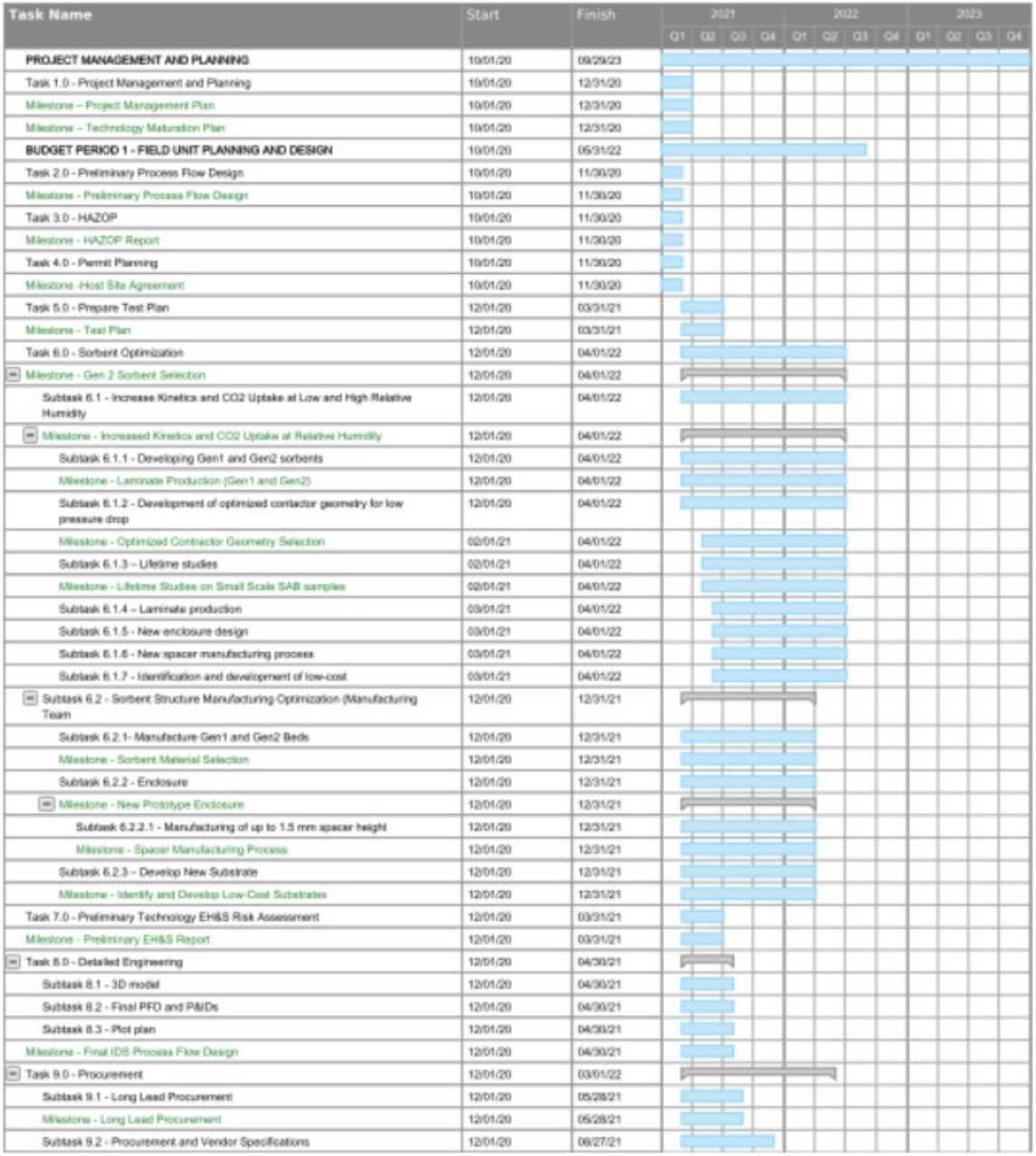
Overall

- Gen2 ambitious kinetics and equilibrium targets achieved at lab-scale demonstration unit at an early stage of this program.
- Major progress towards manufacturing of higher spacers achieved.
- Development of test plant is progressing.

Appendix A: Organization Chart



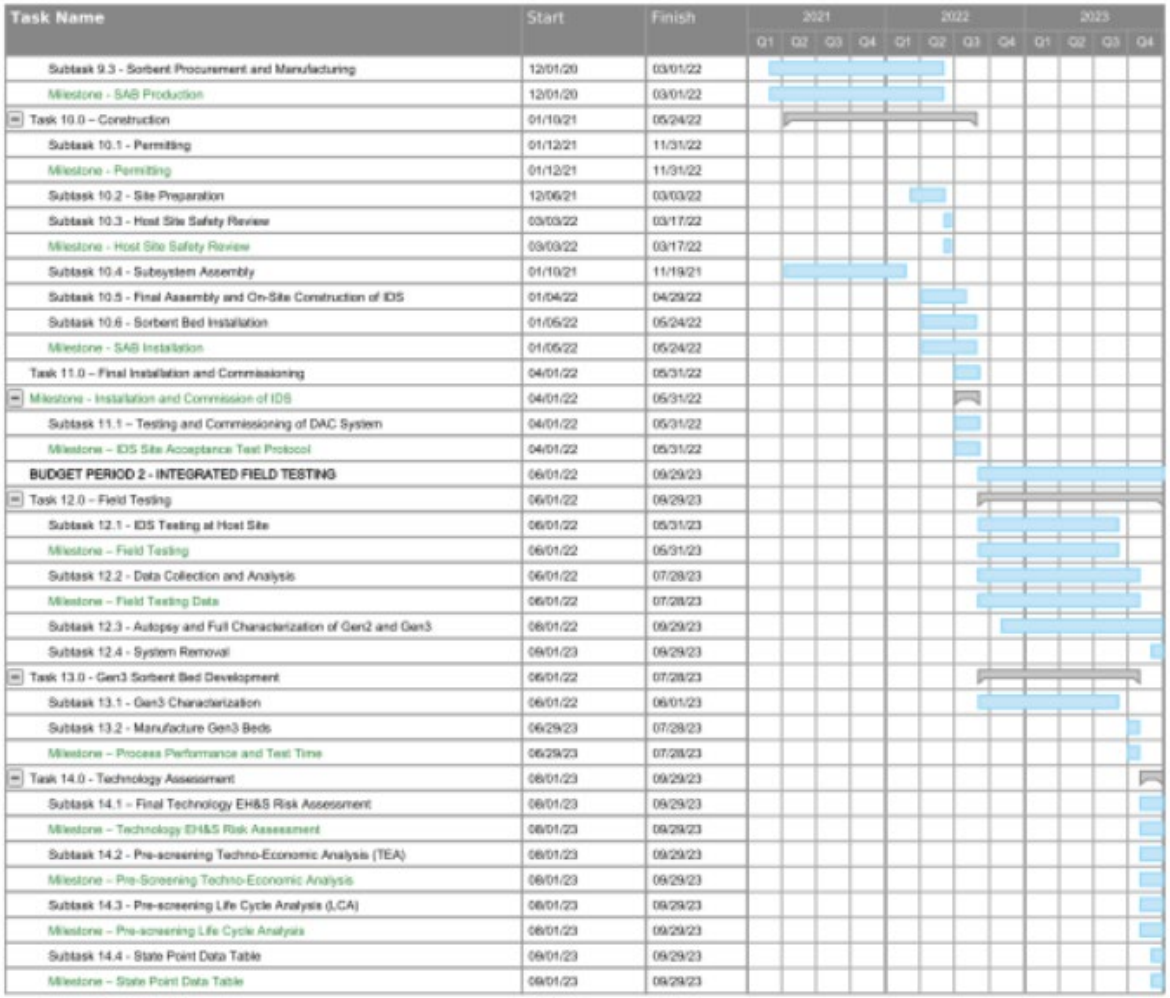
Appendix B: Gannt Chart



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 - Pilot 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

2021 2022 2023
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4

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