Department of Energy Agreement:
No. DE-FE0031952

Direct Air Capture Using Novel Structured Adsorbents

2023 Carbon Management Project Review Meeting

August 29, 2023

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Speakers: Kathy Fagundo, Electricore
Adelaide Calbry-Muzyka, Climeworks
Pierre Hovington, Svante

Acknowledgement
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Project Overview
Cooperative Agreement No.: DE-FE0031959

- Award Period: 10/1/2020 through 09/30/2023

- Project Funding
  - Total Funding: $4,830,280 (**BP1**: $3,467,087; **BP2**: $1,363,193)
  - Federal Funding: $3,098,582 (**BP1**: $2,127,623; **BP2**: $970,959)
  - Cost Share Funding: $1,731,698 (33.12%) (**BP1**: $1,339,464; **BP2**: $392,234)

- Project Participants
  - Prime: Electricore, Inc.
  - Design and Operation: Climeworks AG (Kiewit contracted as a vendor)
  - Technology: Svante, Inc.
  - Host Site: Kiewit
  - Cost Share Contributor: SoCalGas

- DOE-NETL Team
  - Project Manager: Mr. Zachary Roberts
  - Contracting Officer: Ms. Angela Harshman
  - Award Administrator: Ms. Jennifer Burbage

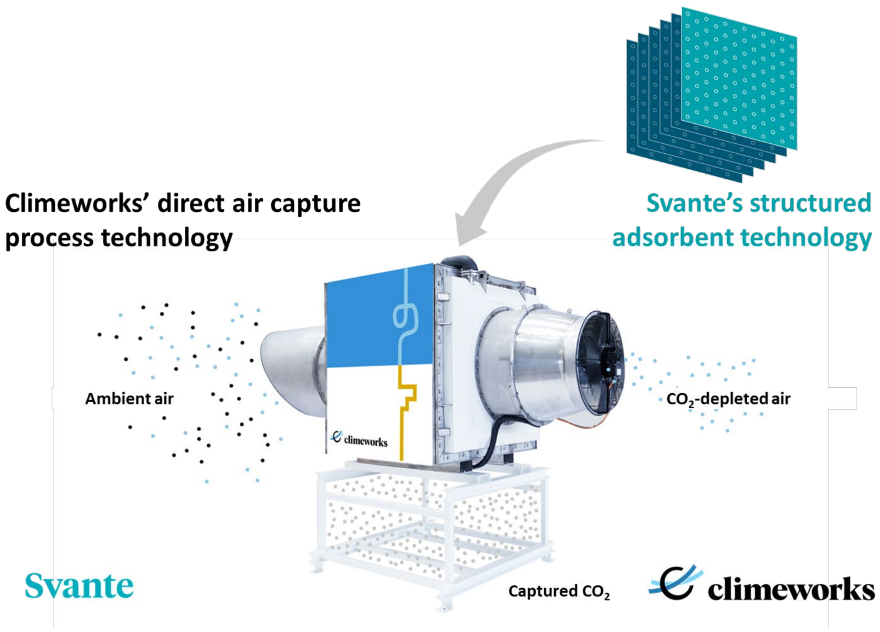
Project Objectives

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.

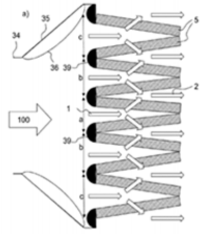
The team will design, build and operate a 30 kilogram per day (kg/day) integrated field test unit capable of producing a concentrated CO_2 stream of at least 95% purity at a facility California.

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

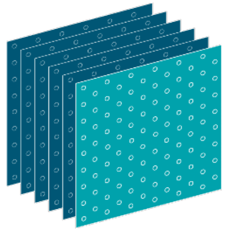
Technology Background: Laminate beds for DAC



climeworks



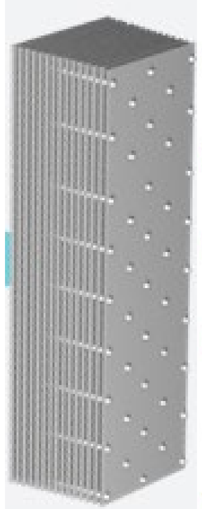
Svante



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)

Svante has 15-year first mover advantage

Business snapshot



- **15+** Years of research and development creating a commercially viable way to capture CO_2 for hard-to-abate industries using tailor-made nano-materials
- **84%** Of the broader carbon capture and removal market targeted through "Picks and Shovels" business model[1]
- **50%** Targeted capital cost advantage of Svante contactor versus equivalent liquid amine carbon capture equipment
- **122** Global patents providing strong IP protection on technology and design
- **160** Best-in-class team of experts led by Mr. Claude Letourneau

World renowned customers

climeworks
HOLCIM
Chevron
SUNCOR ENERGY
cenovus ENERGY

Best-in-class partners

Kiewit
BASF The Chemical Company
T.EN TECHNIP ENERGIES

"Thought leader" investors

TEMASEK
bdc
Chevron
OGCI CLIMATE INVESTMENTS
SUNCOR ENERGY
CARBONDIRECT
THE RODA GROUP
CHART

Svante footprint

Capture plants | Facilities

Lafarge 200 Series Demo Unit
Richmond, B.C., Canada
Capacity: 365 tpa
Status: Operational
Source: Cement Kiln
Owner: Lafarge

Cenovus Pilot Plant
Lloydminster, SK, Canada
Capacity: 10,000 tpa
Status: Operational
Source: NG boiler
Owner: Cenovus

HQ, Engineering and Manufacturing Facilities
Burnaby, B.C., Canada
Capacity: 10 mmtpa
Size: 140,000 sq ft
In-service: Q4 2022
Staff: 250+

Current manufacturing and R&D centres
Burnaby, B.C., Canada
Capacity: 40,000 tpa
Size: 39,000 sq ft
Status: Operational
Staff: 150+

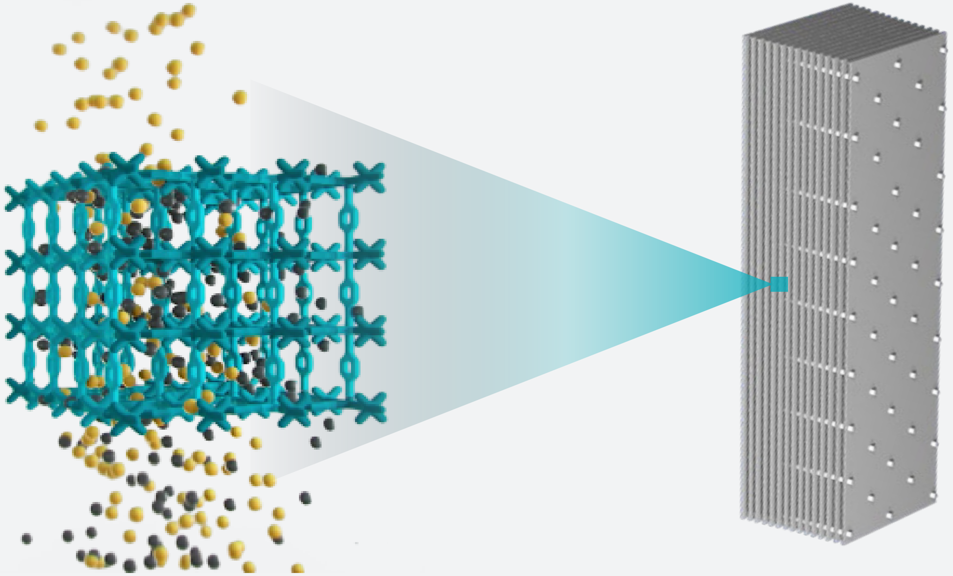
Chevron SOAK 400 Series Plant
San Joaquin, CA, USA
Capacity: 9,125 tpa
Status: Start-up
Source: NG boiler
Owner: Chevron

Note: [1] Removal refers to DAC and BECCS and excludes nature-based solutions

Svante high Kinetics/High Capacity Structure laminates

High Sorbent Flexibility

- Different type of solid sorbent can be used
  - MOF
  - Amines based
  - Porous amine polymer



Structured Adsorbent

- Formed into thin films and stacked into solid filter
- Optimized additives to keep the CO2 capacity and kinetics of the sorbent
- Repeatable, modular and scalable
- Direct heating using low-grade steam

The high modularity and easily scalability of Svante structure laminate technology permitting the use of different solid sorbents for all CO_2 application ranges (from DAC to point sources)

Task 13

Climeworks' DAC leadership

300+ Climeworkers
dedicated to fighting **global warming**

$810 million raised

> 100,000 hours operational experience

< 10% life cycle emissions
renewable energy powered

Climeworks plans continuous DAC+S capacity increase

	2021	2024	2027	2030s	2050
	Iceland Hellisheiði	**Iceland** Hellisheiði	Global	Global	Global
Deployed nominal DAC+S capacity	**4,000 tons** per year	**+36,000 tons** per year	**~ 400,000 tons** per year	**Multi-megaton range**	**Gigaton range**
Location & status	Iceland, operational	Iceland, in construction	TBC, in planning	TBC	TBC
Flagship DAC+S plants	 **Orca**	 **Mammoth**			

~10x scale-up (2021 → 2024)

~10x scale-up (2024 → 2027)

Enable scale-up (2021–2024) · **Global roll-out** (2027) · **Global scale-up** (2030s–2050)

Technical Approach/Project Scope

Combined optimization of sorbent, structure, process –
all demonstrated in field for parametric variation and life testing, reaching TRL 5.

Optimization of sorbent/geometry/process to deliver 3 "generations" of technology

Improve DAC kinetics & capacity (sorbent)

+

Decrease flow resistance for DAC (geometry)

Gen1:
Point-source CO_2 sorbent; point-source spacing

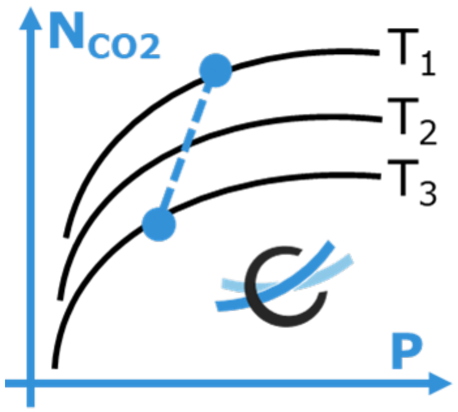
Gen2:
DAC sorbent for humid air; higher spacing

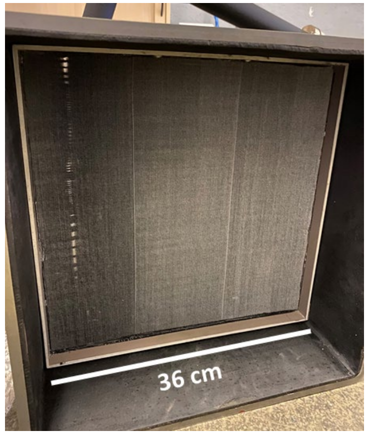
Gen3:
DAC sorbent weather-stable; higher spacing

Used during TRL5 field test (Gen2, Gen3)

TRL 5 demo: Integrated DAC System (IDS) field test for best 2 sorbent "generations"

Phase 1: Parametric testing for process optimization	Phase 2: Life testing

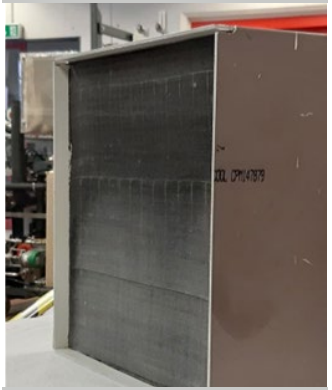




Sorbent optimization, Test facility construction & commissioning

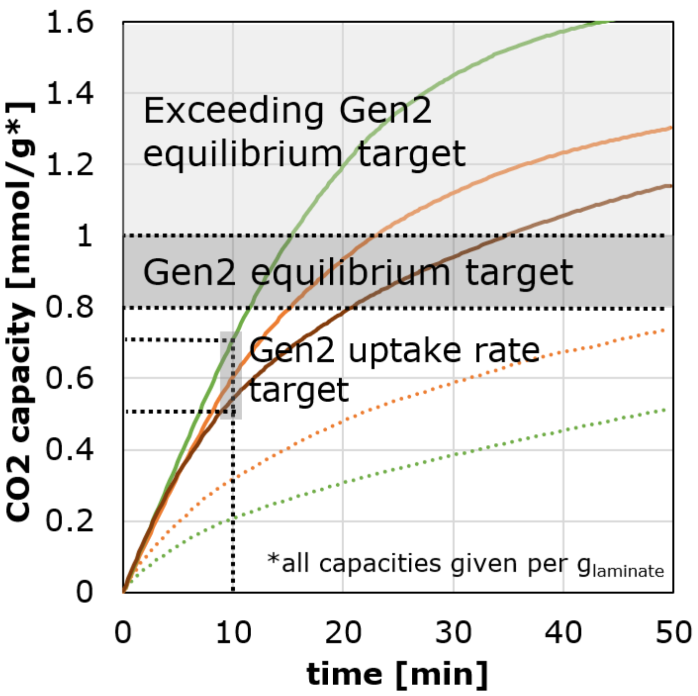
Gen2: performance in Climeworks DAC cycling in pre-tests

Test bed scale:
360x360 mm inlet area



Test facility:
Climeworks in-house facilities in Zurich

Gen2 (Svante structure + Climeworks sorbent)



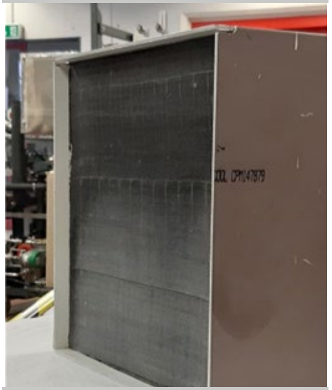
NB: breakthrough run longer than in an optimized cyclic process, to study CO_2 equilibrium capacity.

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

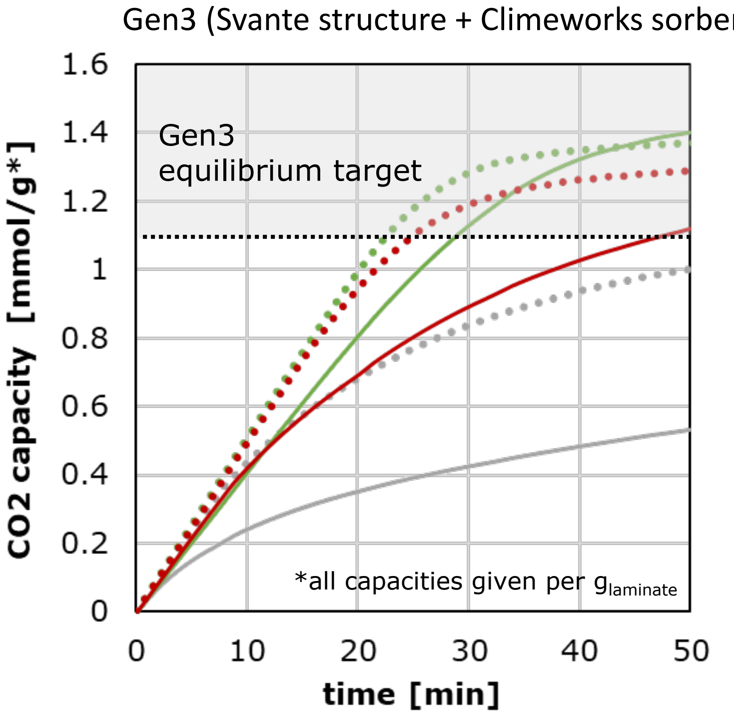
Task 6

Gen3: performance in Climeworks DAC cycling in pre-tests

Test bed scale:
360x360 mm inlet area



Test facility:
Climeworks in-house facilities in Zurich

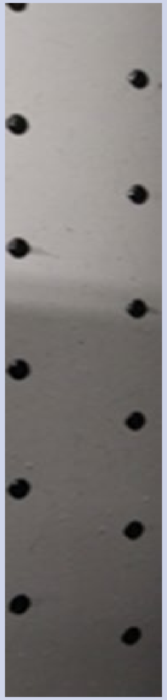


RH = relative humidity

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

Significant improvement of <u>performance stability</u> of Gen3 over Gen2 across air humidities.
Ambitious target capacities of Gen3 reached or nearly (>90%) reached across air humidities.

Svante manufacturing spacers for DAC-optimized geometry

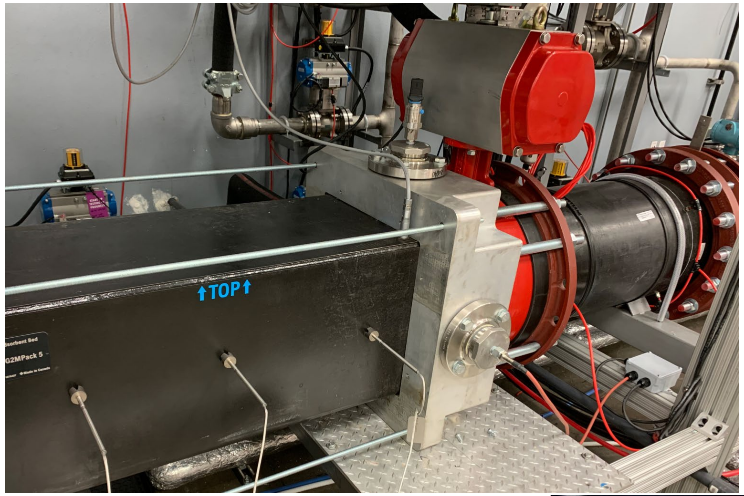
	Gen1 bed & G2MPACK1 spacers	G2MPACK2 spacers	G3MPack
Printer type	Rotary spacer printing	Linear Spacer printing	Linear Spacer printing
Material	Resin	Ceramic	Ceramic
Shape	Dome	Cylinder	Cylinder
Surface	Curved	Flat	Flat
Height increase vs. flue gas optimized spacers	N/A	1.5x-2x	2x-3x
Progress	N/A	Medium-spacer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

Task 6

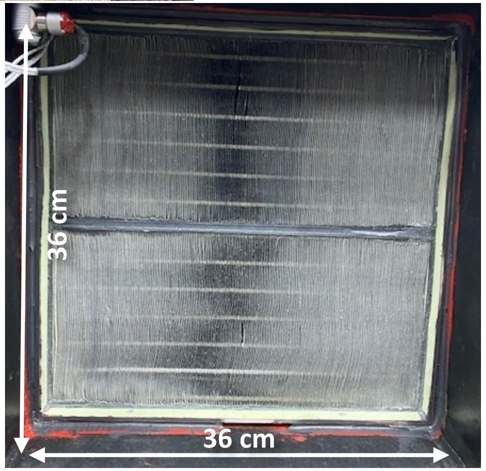
Integrated DAC System (IDS) test plant for TRL 5

Test plant built with 3 independent parallel lines for DAC cycling:

Svante laminate beds loaded:



Bed inlet:

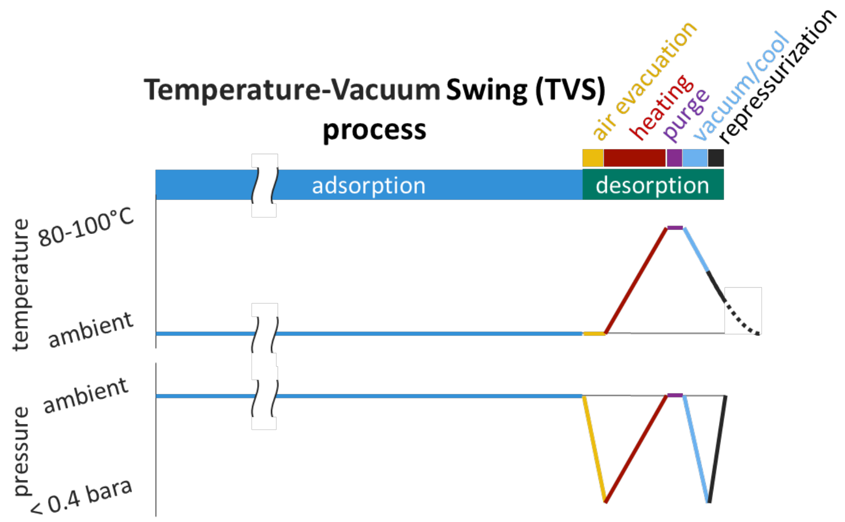


Task 9, Task 10

Test facility operation

Performance targets in DAC cycling in IDS

DAC process used in this project:



Performance targets in IDS:

	BP2 Target [Gen 2]	*BP2 Target [Gen 3]*
Equilibrium cyclic capacity [mol-CO_2/kg-laminate]	0.8-1	1.1-1.6
Pressure drop [Pa]	800-1000	400-700
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%

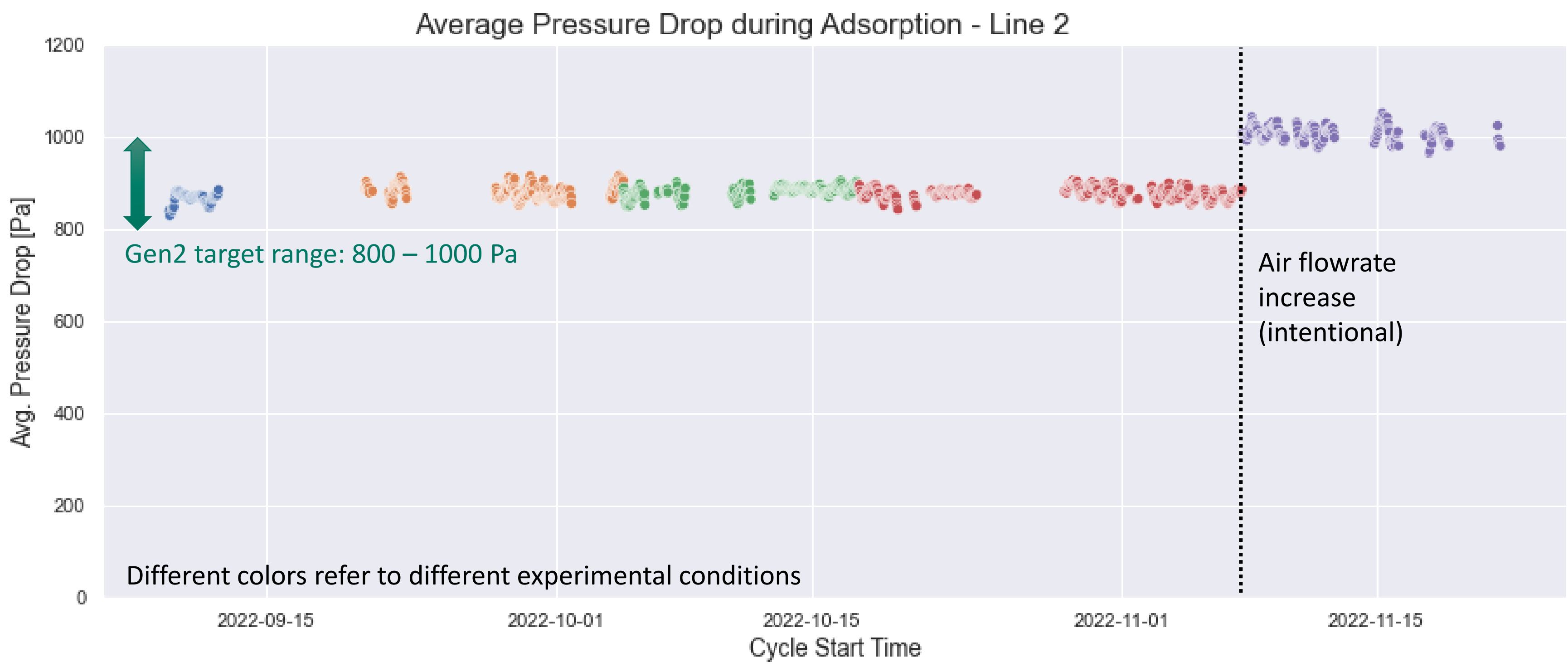
Experimental approach in the IDS's independent lines:

1. **Variation of adsorption & desorption process conditions for process optimization**
2. **Life/durability testing under fixed operating conditions**

IDS was operated successfully over a one year period.

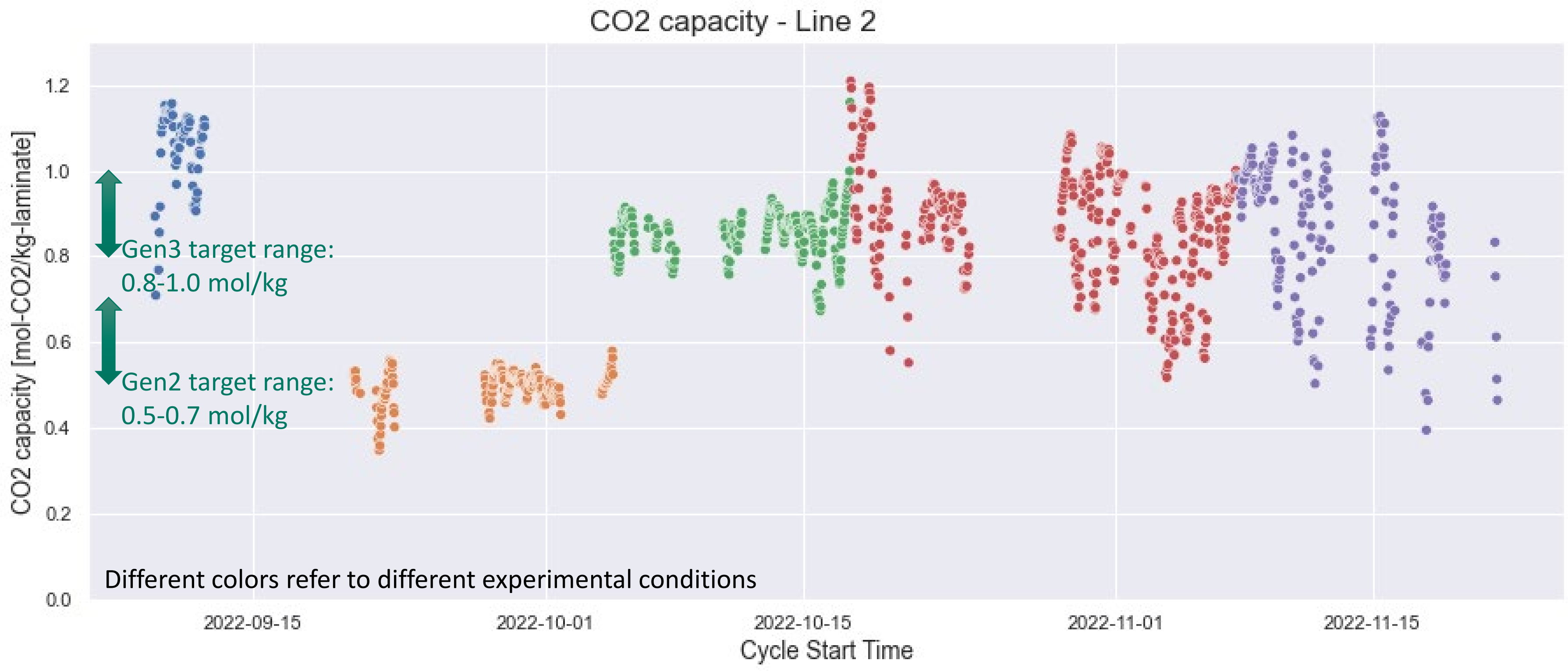
Focus on Gen2 results in this presentation; Gen3 analysis still ongoing.

IDS: Gen2 process condition variations



- **Each data point is one complete cycle**
- **Gen2 target pressure drop is reached and maintained**
- **Pressure drop is steady in time over several weeks if air flowrate is kept constant → good stability of the bed.**

IDS: Gen2 process condition variations

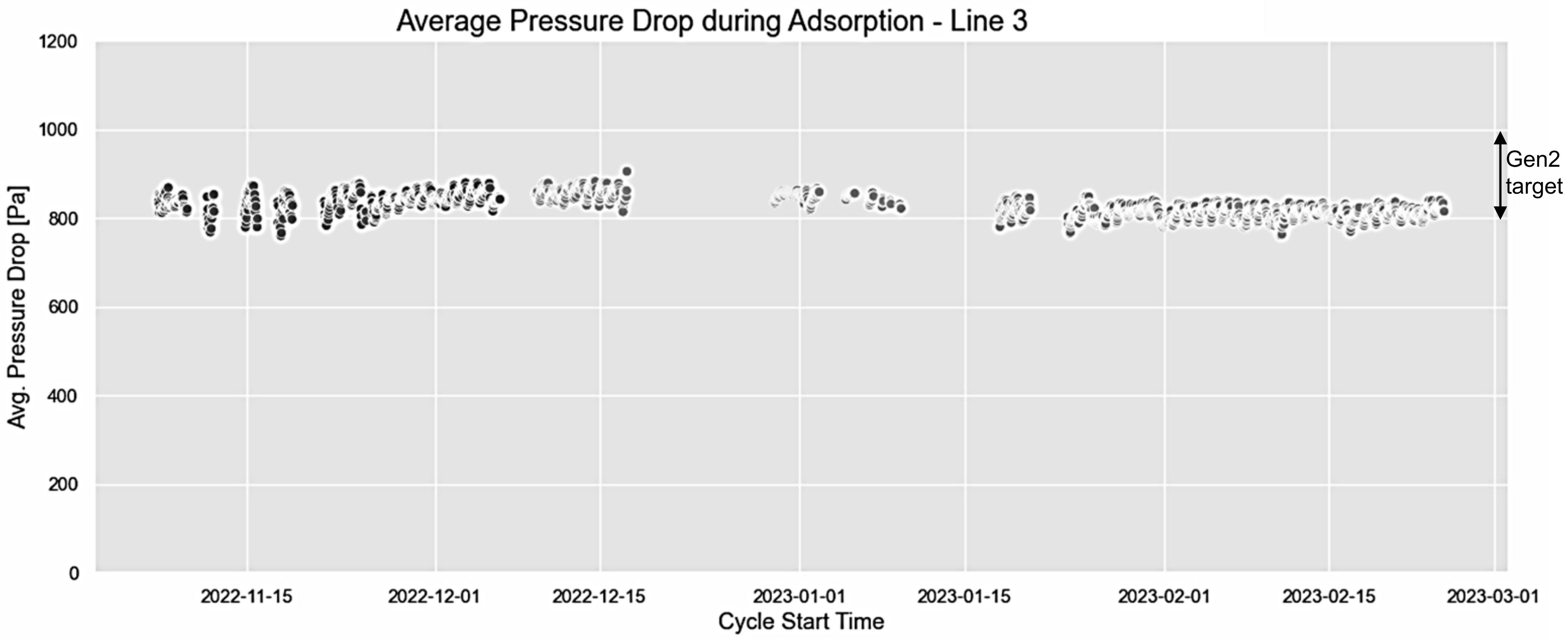


- **Each data point is one complete cycle.**
- **Gen2 target cyclic capacity is met and easily exceeded, even meeting Gen3 targets in many cases.**

IDS: Gen2 process condition variations

- **Each data point is one complete cycle.**
- **Gen2 target uptake rate for CO_2 is met and sometimes exceeded.**

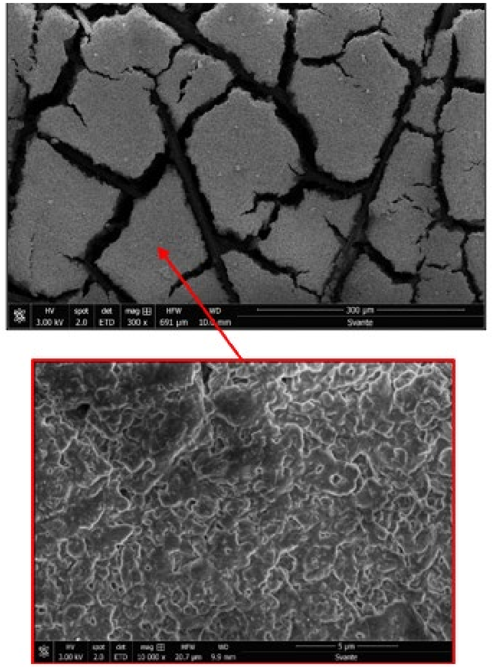
IDS: Gen2 durability testing



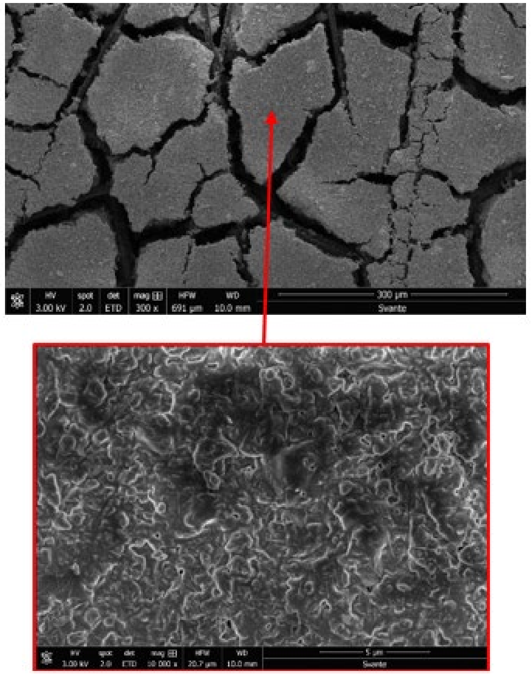
- **Accelerated testing is used here to accumulate more cycles in a shorter period of time.**
- **Each data point is one complete cycle. Durability testing is complete at >3000 cycles.**
- **Gen2 target pressure drop is steady in time over several months → good stability of the bed.**

IDS: Gen2 durability testing

Before IDS operation

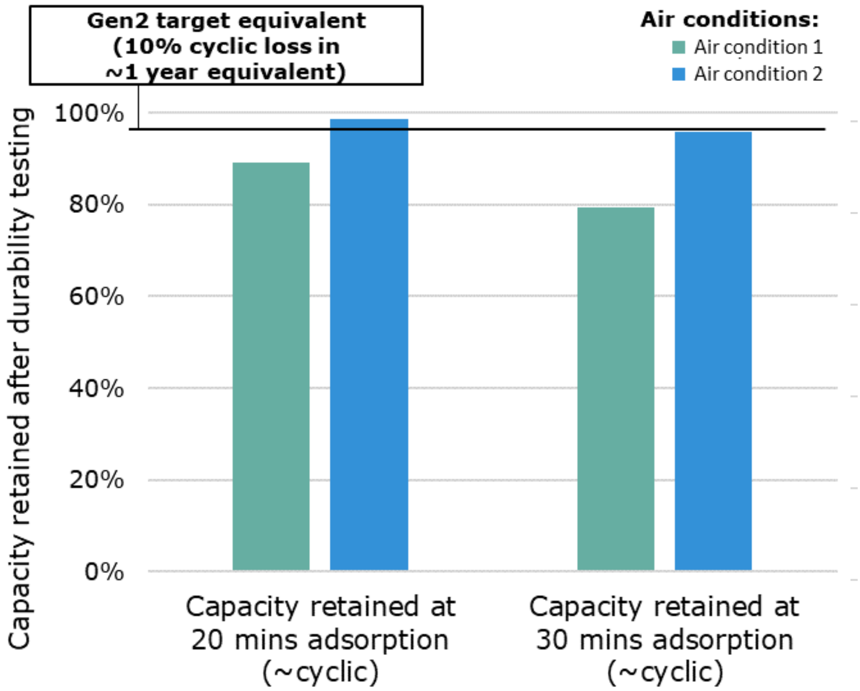


After IDS operation



- **Photos above show the steam inlet side of the Gen2 durability testing bed before and after >3000 cycles in IDS.**
- **Photos confirm the mechanical integrity of the bed, as suggested by the pressure drop stability.**
- **Micrographs confirm the mechanical integrity of the laminates themselves.**

IDS: Gen2 durability testing



- **Can't rely solely on IDS capacity stability: weather's effect on CO_2 capacity cannot be separated from intrinsic sorbent capacity changes.**
- **Instead, bed was characterized before and after IDS operation under fixed weather conditions.**
- **<u>Gen2 target can be met</u>; air weather conditions have an impact.**
- **<u>Post-analysis:</u> FTIR analysis confirms presence of oxidation, more significant on the air inlet side than steam inlet. Several mitigation options (process, sorbent) are in development beyond this project.**

Closing

Project Summary

Completed so far

Having started at TRL4 at the start of the project...

- 3 generations of sorbents were optimized for DAC
- Laminate bed geometry was optimized for DAC
- Gen2 and Gen3 KPIs were met in pre-tests in Zurich
- **Designed, built, commissioned a test facility ("IDS") in California, then operated it successfully over 1 year**
- Gen2 parametric KPIs met or exceeded in cyclic operation in IDS *(& Gen3 KPIs nearly all met*)*
- Durability testing to >3000 cycles was completed for Gen2, and to >5000 cycles for Gen3

…achieving TRL5 and significant technology improvement.

**not reported here; data compilation ongoing*

Remaining to complete

Closing out the IDS operation:

- Gen3 final data analysis
- Gen3 durability testing post-characterization
- IDS decommissioning

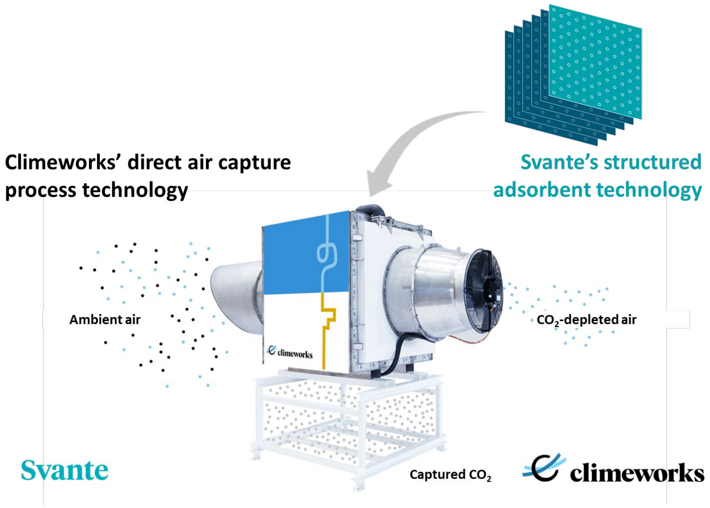
and completing the technology assessment:

- Completion and submission of
  (1) State-Point Data Table
  (2) Prescreening TEA
  (3) Prescreening LCA
  (4) EH&S Risk Assessment
  (5) Updated TMP

Lessons learned

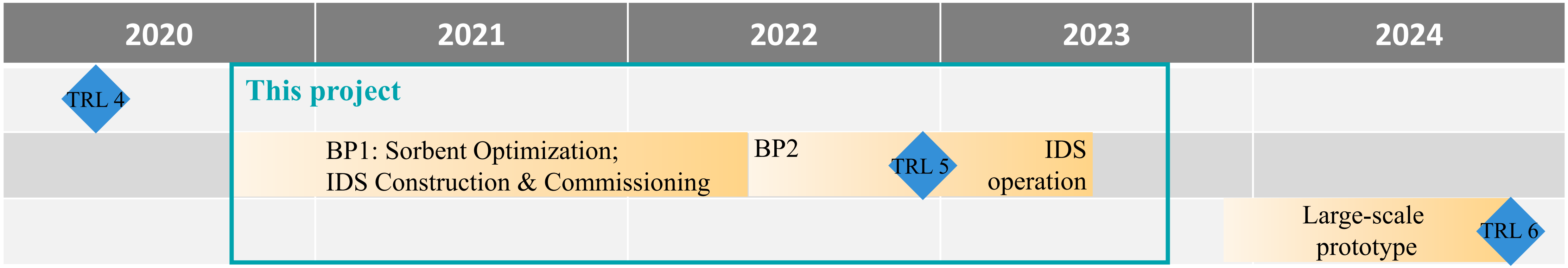
- **Don't underestimate site development:** Original host site change caused delay and additional cost share.
- **Sorbent quantities:** During development, have more sorbent available than you think you will need.
- **Plan for DAC weather dependence:** Think of ways to turn your specific field results into location-independent learnings.
- **Durability testing is essential:** Start durability testing work in parallel with other development work, even if not all parameters are finalized.
- **Auxiliary systems matter:** The longest testing interruptions in IDS were due to an auxiliary compressed air system, nothing to do with DAC – but causing DAC downtime.

Future plans: technology beyond this project



Technology maturation next steps:

- Scaling up the combination of Svante laminates and Climeworks DAC process
- Scaling up the production of Svante laminates and of Climeworks DAC plants
- Other technologies necessary for plant scale up (balance of plant equipment, foundation, etc.) are technically mature.



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

electricore

For more information contact:
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Phone: 661.607.8319

Project Schedule & Success Criteria

Budget Period 1:

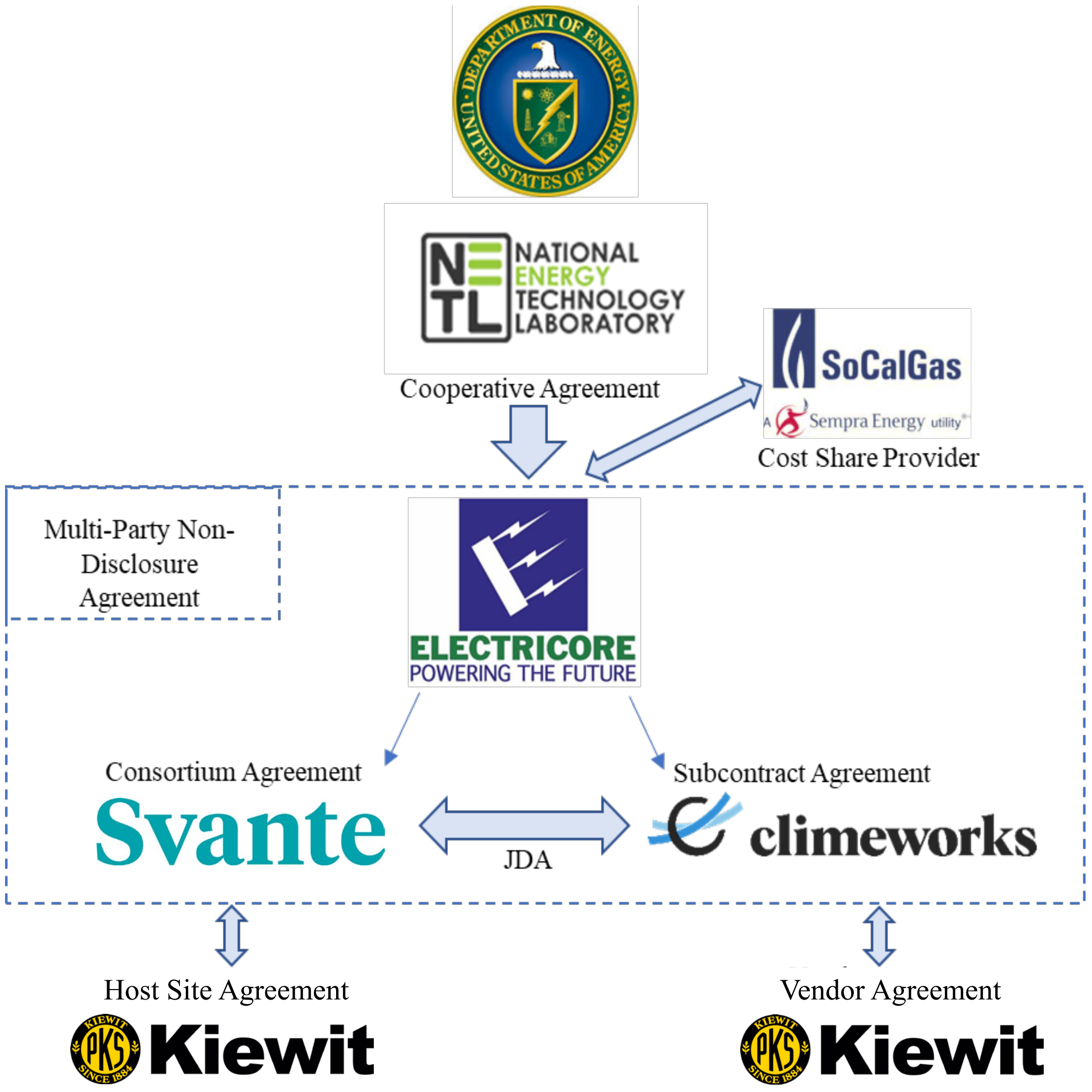
- 10/1/20 – 5/31/22
- Planning, Sorbent Selection, Engineering, Construction, and Commissioning

Budget Period 2:

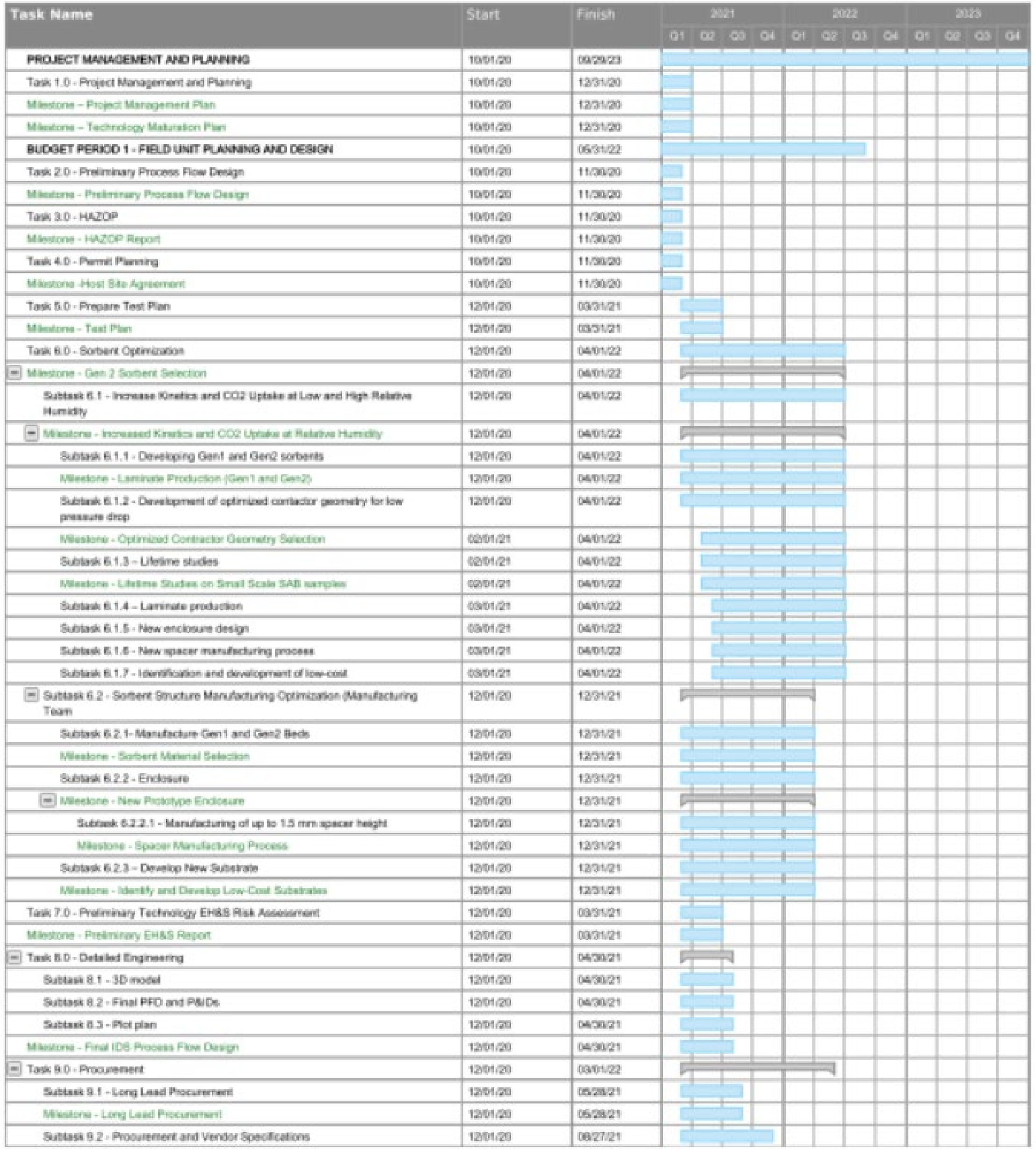
- 6/1/22 – 9/30/23
- Integrated DAC System (IDS) Field Testing, Gen3 Sorbent Bed Development, and Technology Assessment

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

Appendix A: Organization Chart

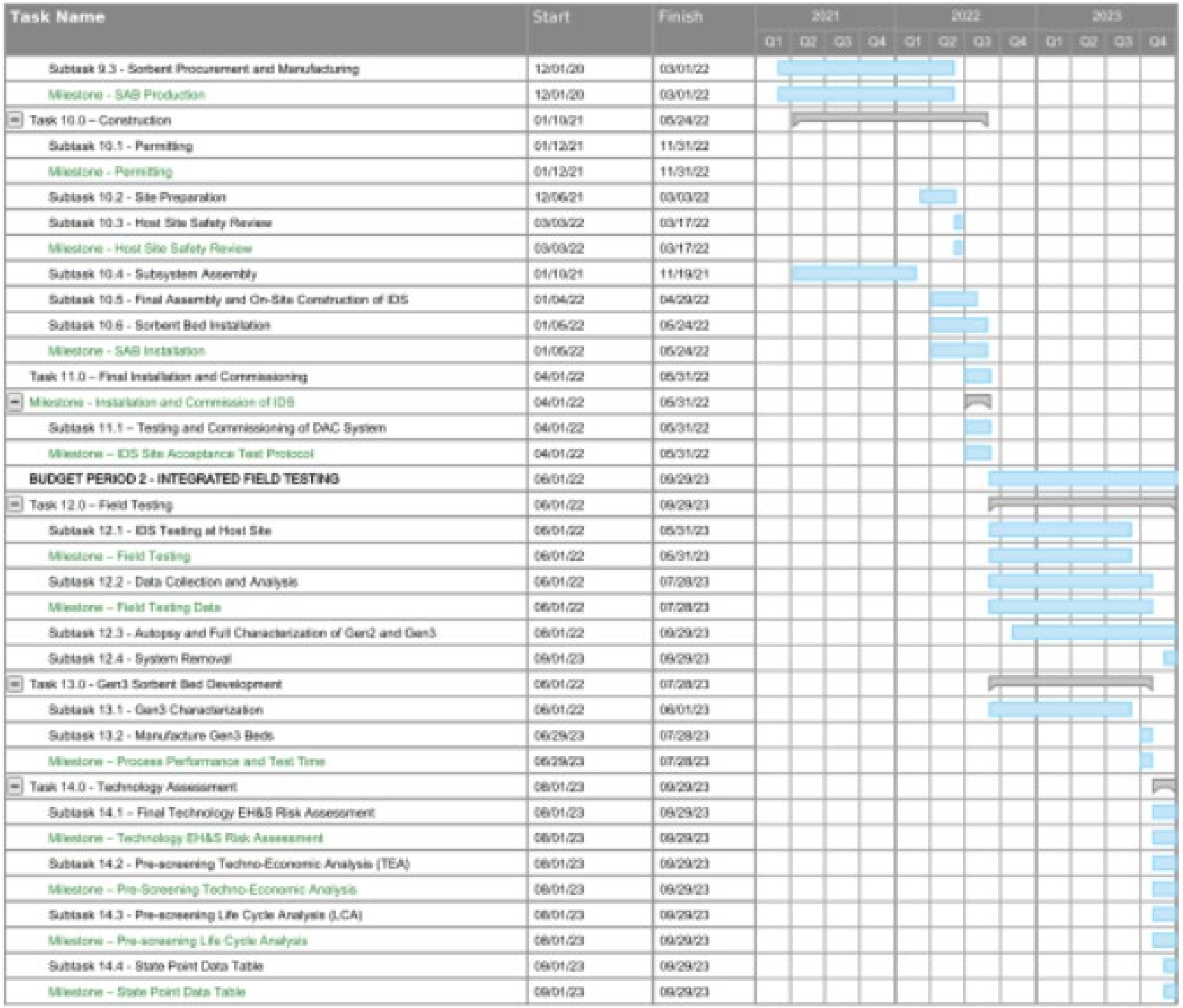


Appendix B: Gannt Chart



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: Gantt 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	08/01/22	09/29/23
Subtask 12.4 - System Removal	09/01/23	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	08/01/23	09/29/23
Subtask 14.1 – Final Technology EH&S Risk Assessment	08/01/23	09/29/23
Milestone – Technology EH&S Risk Assessment	08/01/23	09/29/23
Subtask 14.2 - Pre-screening Techno-Economic Analysis (TEA)	08/01/23	09/29/23
Milestone – Pre-Screening Techno-Economic Analysis	08/01/23	09/29/23
Subtask 14.3 - Pre-screening Life Cycle Analysis (LCA)	08/01/23	09/29/23
Milestone – Pre-screening Life Cycle Analysis	08/01/23	09/29/23
Subtask 14.4 - State Point Data Table	09/01/23	09/29/23
Milestone – State Point Data Table	09/01/23	09/29/23