Direct Air Capture-Based Carbon Dioxide Removal with U.S. Low-Carbon Energy and Sinks

primary project goal

The University of Illinois is leading a team to develop preliminary designs for large-scale direct air capture (DAC) plants that separate and permanently store 100,000 tonnes/yr net carbon dioxide (CO_2) from the air at three different facilities located in Wyoming, Louisiana, and California. The project goal is to examine the effect of various climatic conditions on the DAC system design and overall cost and evaluate the impact of using different low-carbon energy sources (i.e., geothermal, solar, wind, or waste heat). Further, this work aims to tackle scale-up challenges related to construction, operation, and logistics, as well as gauge the technical and regulatory challenges at each site.

technical goals

- Perform an initial engineering design, techno-economic analysis (TEA), life cycle analysis (LCA), business case analysis, and an environmental health and safety (EH&S) analysis for a commercial-scale carbon capture and storage (CCS)-DAC system to capture 100,000 tonnes/year net CO_2 from the air. Produce the designs for the three proposed host site locations.
- Prepare a capital cost estimate (Class IV) for a CCS-DAC system for each of the host sites. Use the capital costs to estimate $/tonne CO_2 net captured.

technical content

Globally, eight countries and states have legally binding net-zero targets, supported by 127 countries and states with net-zero goals (not yet legally binding). Private industry is also reacting, with more than 1,300 companies having net-zero targets (as of January 2022). Globally, net-zero commitments cover at least 68% of the global economy (USD $84.6 trillion). Meanwhile, recent scientific analyses support a widespread, massive investment in DAC deployment as a solution to the climate crisis. Climeworks is the world's first company to demonstrate DAC in combination with geological CO_2 storage (Figure 1) and has successfully created a business model based on the sales of carbon dioxide removal (CDR) services. Climeworks has remained the global market leader in this area, continuing to operate the world's only pre-commercial-scale DAC systems today, and continuing to add to its CO_2 capture capacity. Strategically, Climeworks prioritizes climate-positive CDR.

program area:
Carbon Dioxide Removal

ending scale:
pre-FEED

application:
Direct Air Capture

key technology:
Sorbents

project focus:
Scale-up of Climeworks' Sorbent-Based DAC Technology

participant:
University of Illinois

project number:
FE0032100

predecessor projects:
N/A

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17%

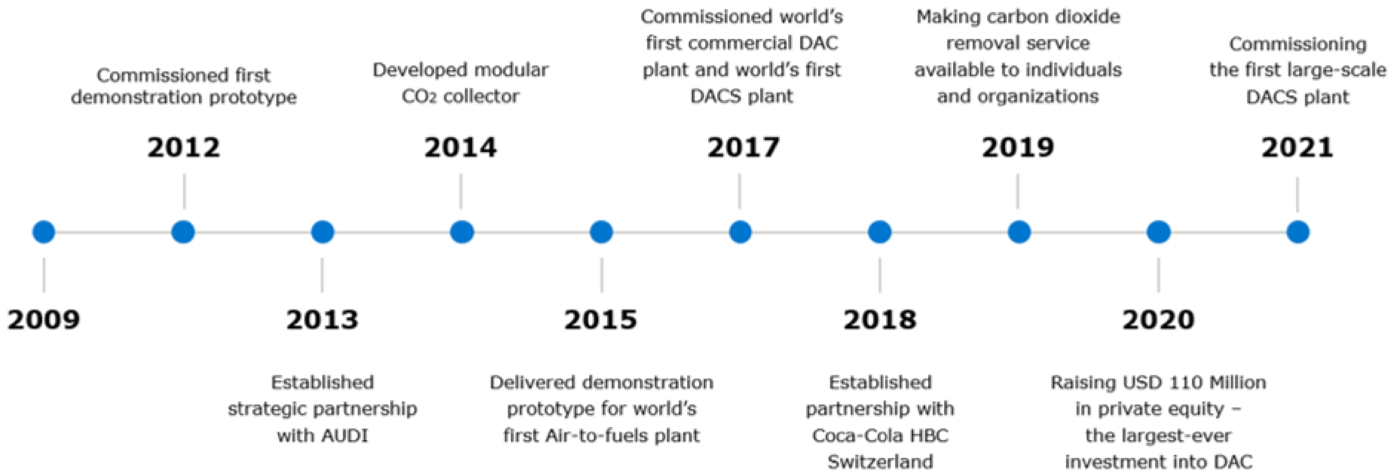

Figure 1: Climeworks' company history. (DACS = direct air capture with storage.)

Climeworks' DAC plants capture atmospheric CO_2 by applying a cyclic vacuum-temperature swing adsorption and desorption process, described below and schematically illustrated in Figure 2.

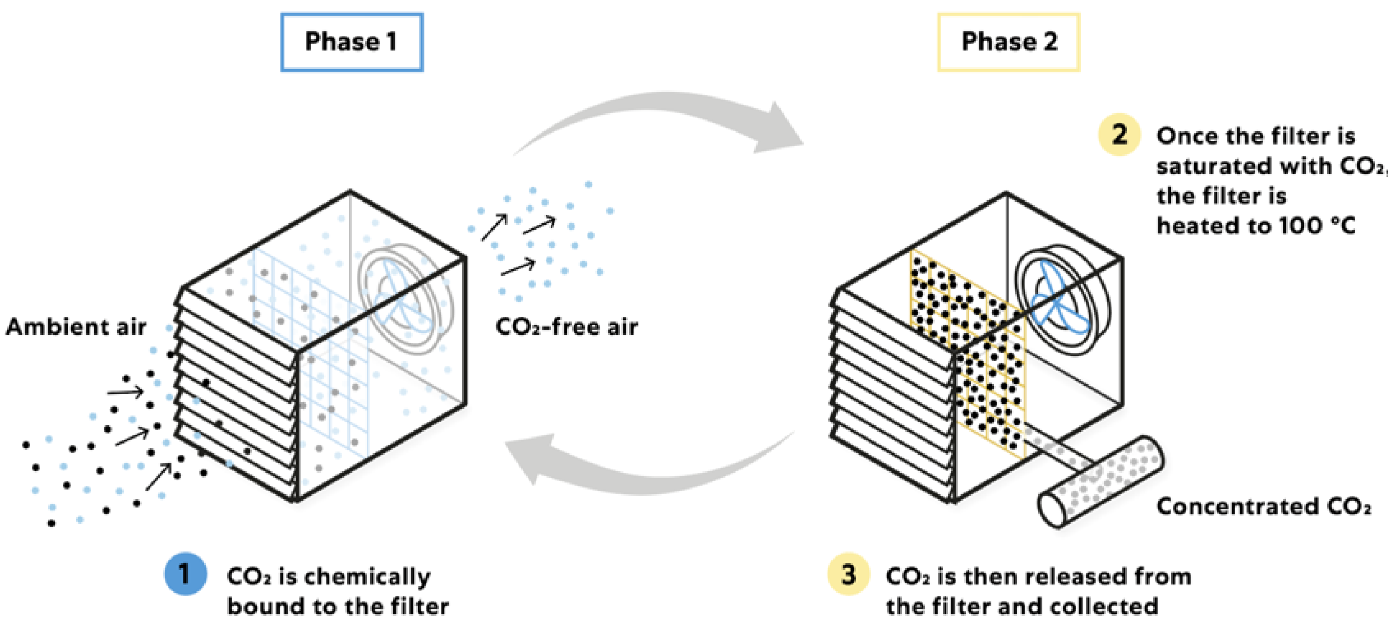

Figure 2: Working principle of Climeworks' DAC technology. Phase I produces CO_2-depleted air and binds the CO_2 on the filter. Phase II produces pure CO_2 and regenerates the sorbent.

Phase I (Adsorption): Air is drawn into the plant using fans and the CO_2 within the air is chemically bound to the sorbent, a highly selective filter material, henceforth also referred to as "filter." Carbon-dioxide-depleted air is released back into the atmosphere.

Phase II (Desorption): Once the filter is saturated with CO_2, it is heated under vacuum to around 100°C using low-grade heat as an energy source. The CO_2 is then released from the filter and collected as a concentrated gas and the continuous cycle is ready to start again. The filter material lasts for several thousand cycles (i.e., several years).

This technology is based on a decade of research and development (R&D) activities, largely in collaboration with world-leading research institutes at the Swiss Federal Institute of Technology (ETH Zurich) and the Swiss Federal Laboratories for Materials Science and Technology. The filter material is arranged in a patented adsorber structure (called "contactor") optimized for low pressure drop and high air flow rates in order to maximize CO_2 capture at the lowest fan electricity cost.

These contactors are contained inside so-called "CO_2 collectors," where the filter is exposed to ambient air in Phase I and where the CO_2 is subsequently extracted from the filter in Phase II, as shown schematically in Figure 2 above.

Climeworks' proven technology has captured CO_2 from air at a pre-commercial scale for more than three years, at 24/7 operation, for a capacity of about 900 tonnes CO_2/year at Climeworks' Beta plant in Hinwil, Switzerland (Figure 3). Scale-up and further cost reductions are now the largest challenges for this technology to meet the increasing global demand for negative emissions. Currently, Climeworks is building the world's largest DAC facility (Orca plant, 4,000 tonnes CO_2/year, for storage) in Iceland, commissioned in September 2021.

Figure 3: Climeworks' development history positions its technology for large-scale implementation today.

Climeworks is advancing its scale-up roadmap to demonstrate large-scale commercial-size DAC at up to 100,000 tonnes CO_2/year with this project. In the current generation, the current cyclic adsorption/desorption technology generation is now mature; it has been optimized across collector geometry, adsorption settings, and desorption settings to result in a maximized output per DAC collector unit using current sorbent technology. The DAC collectors' modular nature and the flexibility of the integrated contactor structures ensure that future developments in sorbent technology can be easily integrated into existing hardware.

The case studies for this project represent different climatic conditions as well as a variety of environments for CO_2 storage from saline aquifers to depleted natural gas reservoirs for safe and permanent storage. Furthermore, the energy supply of the DAC plant differs in each case study and represents a broad variety of low-carbon energy solutions.

Definitions:

Atmospheric Air Feed-Gas Assumptions – Update values below to describe the air feed-gas pressure, temperature, and composition entering the capture system:

Pressure	Temperature	Composition						
		vol%					ppmv	
		CO_2	H_2O	N_2	O_2	Ar	SO_X	NO_X
ambient	ambient	0.04	variable	78.09	20.95	0.93	trace	trace

Chemical/Physical Sorbent Mechanism – Amine-based sorbent which binds CO_2 by chemisorption, as described in Phases I/II of Figure 2.

Sorbent Contaminant Resistance – Sorbent is highly resistant to expected contaminants found in the air. Sulfur oxide (SO_X) and nitrogen oxide (NO_X) at levels present in most air streams are not a key driver of degradation.

Sorbent Attrition and Thermal/Hydrothermal Stability – Stability of sorbent over thousands of cycles has been demonstrated by Climeworks' operating DAC plants.

Air Gas Pretreatment Requirements – N/A.

Sorbent Make-Up Requirements – Replacement of sorbent required every three years (equivalent to several thousand cycles).

Waste Streams Generated – Carbon-dioxide-depleted air is emitted from the contactors. Water is treated and reused in the plant (at full-scale).

Process Design Concept – A block flow diagram detailing the two phases of the project is shown in Figure 3.

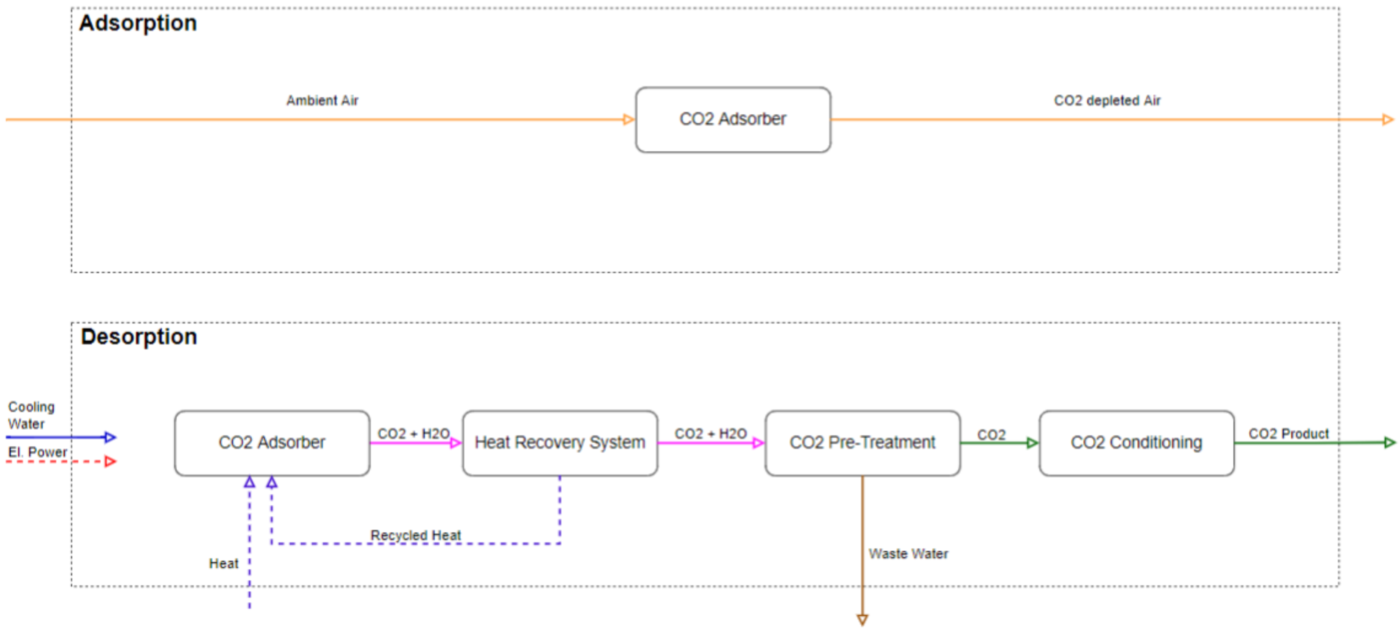

Figure 3: Block flow diagram.

Proposed Module Design – The sorbent is located inside a CO_2 Collector Container (CC). The concept of modular CCs was first developed in 2014 for the first generation of Climeworks plants. Its modularity allows for easy scale-up (the number of collectors can be adapted to match the required capacity per plant) and production can benefit from economies of scale. This CC has the external dimension of an ISO 668 40-ft container, to allow for simpler handling and shipping.

TABLE 2: DIRECT AIR CAPTURE ECONOMICS

Economic Values	Units	Estimate 2035**	Target long-term
Cost of Carbon Removed	$/tonne CO_2	150-210	~100
Cost of Net Negative Emissions achieved*	$/tonne CO_2	170-230	~110
Capital Expenditures	% of total	30-50%	
Operating Expenditures	% of total	50-70%	

*** Including a full life cycle assessment from cradle-to-grave.**
**** At 1 MtCO_2/y single plant scale, with a learning rate consistent with total installed volume of 100 MtCO_2/y assumed.**

Definitions:

Cost of Carbon Removed – Projected cost of capture and storage per mass of CO_2 under expected operating conditions.

Cost of Net Negative Emissions Achieved – Projected cost of capture and storage per mass of CO_2 when accounting for the associated grey emissions.

Capital Expenditures – Projected capital expenditures in percentage of total costs.

Operating Expenditures – Projected operating expenditures in percentage of total costs.

Calculations Basis – Calculations above consider a 1 $MtCO_2$/year single plant, using capital cost values derived from Climeworks' current plants, with scaling factors in the range of 0.6–0.95 depending on the equipment type, with forecasted renewable electricity and heat prices, and with a learning rate assumed for future generations of plants equivalent to a total installed volume of 100 $MtCO_2$/y.

Scale of Validation of Technology Used in TEA – The Climeworks DAC systems consist of three major subsystems: the core technology (optimized sorbent/process combination); the full-scale modular CO_2 collectors, which house the core technology; and the process plant. This project focuses on the improvement of the process plant and optimization of a large-scale plant (layout and equipment optimization).

"Estimate 2035" costs are based on development improvements of the core technology, as well as incremental improvements of Climeworks' current systems for the collectors and process plant, based on field-proven enhancements of the Orca plant in Iceland.

Qualifying Information or Assumptions – A conservative 90% removal efficiency (net-negative emissions CO_2 achieved/CO_2 removed) is assumed, consistent with external LCAs performed of Climeworks' systems.

technology advantages

- Mature plant design, from the extensive experience in designing, constructing, and operating full-system prototypes, as well as up to 4,000 tonnes CO_2/year pre-commercial units.
- Modular design of the CCS-DAC plants enables Climeworks to scale rapidly from a pre-commercial to commercial scale.
- DAC collector modular nature allows flexibility for future developments in sorbent technology, which can be easily integrated into existing hardware.

R&D challenges

- Engineering design of DAC systems at three different host sites with differing climates.

status

The University of Illinois has begun initial engineering design and initial planning, collecting information and requirements for each host site.

available reports/technical papers/presentations

Kevin C. Obrien, "Direct Air Capture-Based Carbon Dioxide Removal with United States Low-Carbon Energy and Sinks," Project kickoff meeting presentation, Pittsburgh, PA, October 2021. *https://www.netl.doe.gov/projects/plp-download.aspx?id=11215&filename=Direct+Air+Capture-Based+Carbon+Dioxide+Removal+with+United+States+Low-Carbon+Energy+and+Sinks.pptx*.

Kevin C. Obrien, "Direct Air Capture Facility Development in the United States," presented at American University's Assessing Carbon Removal webinar series, February 21, 2022. *https://www.youtube.com/watch?v=HX5c3llo42w*.