# FINAL SCIENTIFIC / TECHNICAL REPORT

***Western Regional Direct Air Capture Hub Pre-Feasibility Study***

*November 12, 2025*

**SUBMITTED UNDER DOE COOPERATIVE AGREEMENT**

DE-FE0032379

**SUBMITTED BY**

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**SUBMITTED TO**

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National Energy Technology Laboratory

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## Executive Summary

Chevron New Energies, a division of Chevron U.S.A. Inc. (Recipient), led a multi-organizational team that included direct air capture (DAC) technology companies, an engineering firm, a university, and a grant administrator to explore the feasibility of a DAC hub initially focused on Kern County, California.

The objective of the Western Regional DAC Hub pre-feasibility study was to assess a portfolio of DAC technologies' maturity, modularity, and applicability to the potential DAC hub concept and develop the initial integrated hub design concept.

The DAC technology companies engaged in the study were 280 Earth, an Avnos entity (Avnos), and Sustaera. Hub integration and balance of plant (BOP) engineering was performed by Black & Veatch. The preliminary life cycle analysis (pre-LCA) was developed by the University of California, Davis (UC Davis). Grant administration activities were performed by Electricore.

The team completed their respective pre-feasibility activities to identify the potential hub location and $CO_2$ transport routes; select anchoring DAC technologies with at least 50,000 net tonnes of $CO_2$ removed annually (50 KTA $CO_2$) per DAC system; develop a conceptual hub design; and perform a pre-LCA for the initial hub capacity. Additionally, the team contributed respectively to develop an initial design for the DAC hub BOP for the final hub capacity with at least 1 million net tonnes of $CO_2$ removed annually (1 MTA $CO_2$).

This report summarizes the initial design concept developed during the study.

## 1.0 Study Objectives

The objective of the Western Regional DAC Hub pre-feasibility study was to assess a portfolio of DAC technologies' maturity, modularity, and applicability to the potential DAC hub concept and develop the initial integrated hub design concept.

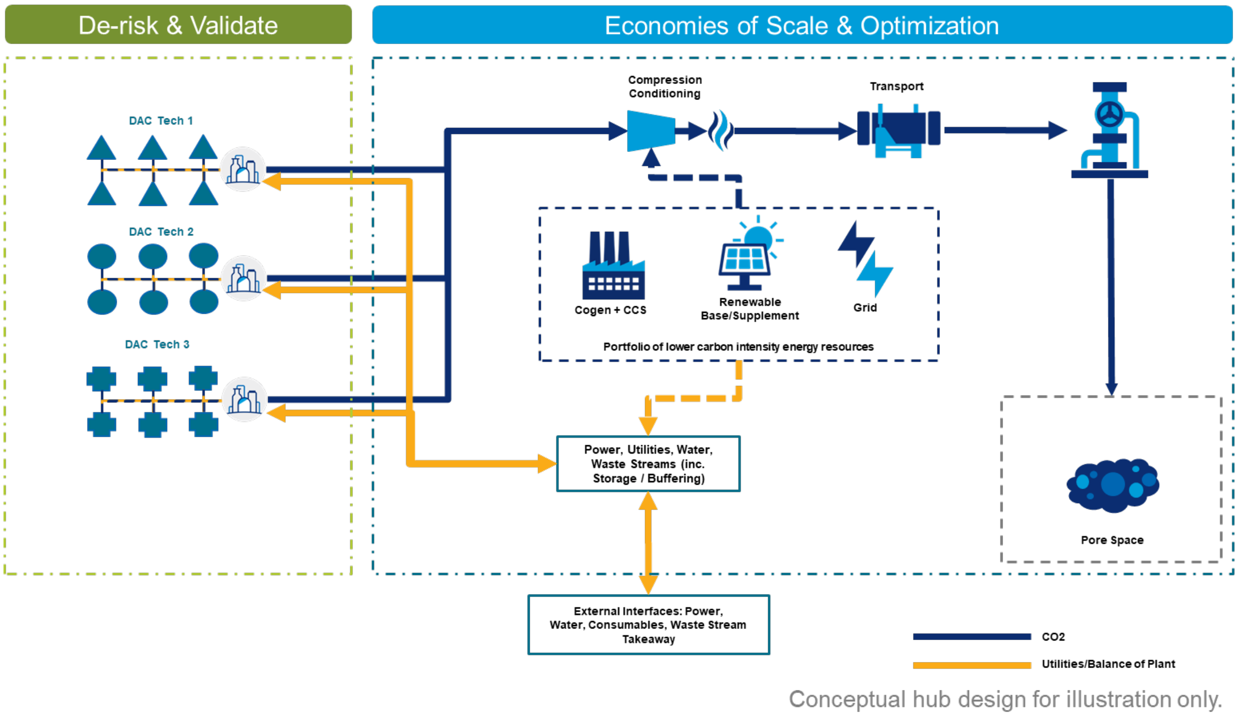



**Figure 1. Western Regional DAC Hub – Illustrative Concept**

## 2.0 Study Basis

The study assessed a phased development of the Western Regional DAC Hub with an initial target capacity of at least 150 KTA net $CO_2$ removal (i.e., at least 50 KTA net $CO_2$ removal per DAC technology system) and later scaling to a final hub capacity of at least 1 MTA net $CO_2$ removal.

Recipient identified a site in Kern County, California as a potential DAC hub location from which to complete the study to capture, transport and permanently store $CO_2$ for both the initial hub capacity and final hub capacity. The hub was assessed as an integrated system with a common ownership structure from capture to transport.

## 3.0 DAC Technology Systems

The DAC technology companies engaged in the study were 280 Earth, Avnos, and Sustaera. During this study, each DAC technology company developed and described an initial DAC system design to inform the BOP and integrated hub design concept. The descriptions, technology readiness level (TRL), scale-up plans, and technology maturation plans (TMP) for each DAC technology can be found in the following appendices:

- Appendix A.1 – 280 Earth Description and Technology Maturation Plan
- Appendix A.2 – Avnos Description and Technology Maturation Plan
- Appendix A.3 – Sustaera Description and Technology Maturation Plan

Each DAC system was evaluated on its technical merits, BOP conditioning requirements, and compatibility within the overall hub design concept. As a result of this analysis, Recipient developed an initial design concept anchored by all three participating DAC technologies.

## 4.0 Initial DAC Hub Balance of Plant Design Concept

Black & Veatch, as the DAC hub engineering integrator, leveraged engineering deliverables from each DAC technology to design an initial BOP concept that complied with the basis of design developed at the beginning of the study.

### 4.1 Initial Design Concept

The initial BOP design concept included $CO_2$ conditioning, compression, and pipeline transport to the storage site location. Black & Veatch also evaluated initial utility and energy requirements based on this design concept which influenced the energy strategy analysis and pre-LCA results.

The design concept for the final hub capacity build-out generally assumed a proportional scale up of equipment and utility requirements.

For the energy strategy analysis, this study considered grid power as base case and alternative lower carbon intensity energy sources as enhancements, including installing dedicated solar power and adding post-combustion capture systems to existing natural gas-fired cogeneration facilities. Black & Veatch assisted in evaluating these options and Recipient determined the selected energy strategy for the purposes of the study and the pre-LCA.

A report summarizing Black & Veatch's activities and findings regarding the initial BOP design concept, along with preliminary assumptions made for the BOP capacity build-out, can be found in Appendix B – Initial DAC Hub Balance of Plant Design Concept and Appendix B.1 – Block Flow Diagram.

### 4.2 Safety and Security Requirements

Recipient has a robust, comprehensive set of Health, Safety, and Environmental (HSE) policies and procedures, known as Operational Excellence Management System (OEMS), for large-scale project work. Recipient's OEMS requires Recipient to monitor, assess, and address project-related health, safety, and security (both physical and cybersecurity) risks and impacts.

### 4.3 Regulatory Requirements

Based on the initial DAC hub concept, Black & Veatch developed a preliminary regulatory and permitting matrix to identify relevant federal, state and local requirements as well as the workflow for processing each potential regulatory requirement. This process has identified an initial list of more than 30 potential federal, state, and local permitting activities that may be applicable, each with agency review periods that are estimated to vary from a few weeks to several years.

## 5.0 Preliminary LCA for Initial DAC Hub Capacity

UC Davis developed a pre-LCA to convey a high-level description of life cycle considerations for the initial DAC Hub capacity. This report can be found in Appendix C – Preliminary LCA and represents the views of UC Davis. Recipient does not take an official position with respect to reference material, including the listed life cycle inventory (LCI) data sources and Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) 100-year global warming potential values.

Based on these results, the initial hub design concept demonstrates the potential to achieve at least 150 KTA in net $CO_2$ removal capacity using the selected energy strategy for this study.

It is important to note that the continued refinement of a hub life cycle analysis as a potential design concept matures would be necessary to validate these conclusions.

## 6.0 DAC Hub Data Tables

As a result of the initial design concept development and subsequent pre-LCA, preliminary estimates for the DAC hub data table were completed and included in Appendix D – DAC Hub Data Table.

## 7.0 Storage Field Development Plan

Recipient has provided the status of the potential storage site(s) associated with this DAC Hub study in Appendix E – Storage Field Development Plan. Any work for storage field development was done in parallel but was not funded under the scope of this study.

# Appendix A – DAC Descriptions and Technology Maturation Plans

## Appendix A.1 – 280 Earth Description and Technology Maturation Plan

280 Earth

Technology Description and Technology Maturation Plan

for Western Regional DAC Hub

Cooperative Agreement No. DE-FE0032379

Submitted by

280 Earth, Inc.

## A. Technology Description

280 Earth's DAC technology and system design is created with scaling in mind, supporting our goal of driving down levelized cost of capture (LCOC). The system works by continuously pulling ambient air into contact with a proprietary sorbent that captures both $CO_2$ and water in the adsorption chamber. The $CO_2$-rich sorbent is conveyed to a desorption chamber where it releases the $CO_2$ and water. $CO_2$ is then compressed for permanent storage underground. The system requires no water input; it produces water as it captures $CO_2$. The sorbent is regenerated and returned to the initial adsorption phase.

## B. Technology Readiness Level (TRL)

280 Earth's Direct Air Capture (DAC) technology has achieved a TRL of 7, engineering/pilot-scale system validation in a relevant environment.

In June 2024, the company completed construction of a 500 tonnes per annum (TPA) pilot-scale DAC unit, representing a transition from laboratory-scale testing to technology demonstration in the field. The 500-tpa pilot unit is a 10x step down from the planned 5,000-tpa full-scale module, and this unit is now operating and capturing $CO_2$ in The Dalles, Oregon. The 500-tpa unit is capable of performing all the functions that will be required of the full-scale commercial system, incorporating the DAC technology into an operational system.

280 Earth's commercial DAC technology is designed around 5,000-tpa modules connected in clusters for site buildout and sharing balance of plant infrastructure, eliminating the need to design custom units for each installation. This allows for faster deployment as compared to a "build-to-suit" approach, enabling us to more rapidly reach full scale on large projects such as the Western Regional DAC Hub. 280 Earth's technology is also differentiated by the utilization of low-grade waste heat and production of water. Considering these factors, we target commercial applications defined by 1) opportunities for scaling to 1M+ tpa and 2) availability of partners to provide waste heat and/or to offtake our produced water.

## C. Proposed Work

The Western Regional DAC Hub study work did not include advancement of 280 Earth's TRL. The work included evaluation of the DAC system's existing and projected inputs and outputs to determine the feasibility of incorporating the DAC technology into the proposed Hub. The team evaluated siting requirements such as physical footprint, energy requirements, and manufacturing resources in the context of the proposed hub. As described below, separately from the study, 280 Earth continued to mature the DAC technology during the study timeline.

Key DAC performance attributes relevant to the Western Regional DAC Hub study consisted of needed inputs and expected outputs. For 280 Earth these include energy requirements, capture percentage, water production rate, $CO_2$ product purity, and adsorption/desorption cycle time. 280 Earth's DAC process does not require steam or water as inputs.

As described above, ongoing engineering efforts outside of the study are expected to advance 280 Earth's technology and improve these performance attributes. However, advancement of 280 Earth's TRL was not part of the Western Regional DAC Hub study.

## D. Post-Project Plans

The study proposed to evaluate the feasibility of incorporating 280 Earth's DAC technology into the Western Regional DAC Hub. Advancement of 280 Earth's TRL was not part of the proposed study. Although 280 Earth plans to continue advancing the DAC technology separately from the study, the DAC Hub feasibility study as described in Cooperative Agreement No. DE-FE0032379 could have been completed at 280 Earth's current TRL of 7.

To attain the next TRL, outside of the study, 280 Earth will permit, construct, commission, and operate the first 5,000-tpa DAC module. The 5,000-tpa DAC unit is envisioned as a full-scale, replicable module for commercial deployment. Modules can be connected together in a cluster for site buildout. This module size was selected to allow flexibility to match project size with local characteristics (ex. waste heat availability, sequestration capacity, renewable energy resources, and cooling demand from a partner). The 5,000-tpa module size also allows 280 Earth to utilize a variety of off-the-shelf (OTS) and customized off-the-shelf (COTS) components, maximizing supply chain availability and shortening construction timelines.

## Appendix A.2 – Avnos Description and Technology Maturation Plan

# Technology Description and TMP

## Western Regional DAC Hub

AVNOS

## TECHNOLOGY DESCRIPTION

Capturing commercially significant amounts of $CO_2$ directly from air (DAC – direct air capture) requires movement of a large volume of air through the device. The emerging field of atmospheric water extraction (AWE) similarly involves the movement of large volumes of air. Avnos integrates these two technologies into a single overall process, a hybrid direct air capture system (HDAC) – with the AWE section facilitating operation of the DAC section. This combination gives HDAC the potential to become an economically and environmentally attractive direct air capture technology.

## TECHNOLOGY READINESS LEVEL

Avnos Direct Air Capture (DAC) technology is a compilation of numerous systems with varying levels of technological maturity, including:

- Air Handling Equipment draws air through the $CO_2$ capture media, and is comprised of commonly available Heating, Ventilation, and Air Conditioning (HVAC) components, such as blowers, particulate filters, etc. Maturity level of this equipment is TRL 9.
- Sorbent materials and associated vacuum chambers, engineered for capture of $CO_2$ and water vapor, with a maturity level of TRL 6.
- Balance of plant equipment, including compressors, heat exchangers, and pumps, provide sorbent regeneration and separation of $CO_2$/water vapor. These are proven industrial technologies with a maturity level of TRL 9.

Avnos launched its first field-deployed, integrated pilot Hybrid DAC (HDAC) unit at the end of 2023 with the support of the Department of Energy (DOE) (Award No. DE-FE0031970; Funding Opportunity Announcement No. 0002188). This system was designed for a capture capacity of 30 tons/year and produces 150 tons/year of water. In addition, Avnos is working with the U.S. Office of Naval Research (ONR) to develop a demonstration unit with an increased capacity of 600 tons/year, set to be commissioned in 2025.

Commercial application for Avnos' DAC technology is primarily the monetization of high-quality carbon credits generated by the capture and sequestration of $CO_2$. Water produced by the Avnos' HDAC process has additional revenue potential, particularly in arid regions. Additionally, Avnos's product steams (water and $CO_2$) can serve as feedstock to produce e-fuels, such as sustainable jet fuel, in our next pilot scale projects. This additional facet of the HDAC technology aligns with the world's growing need for renewable and low-carbon alternative fuels.

Avnos is investigating the integration of moisture swing adsorption (MSA) within data centers for $CO_2$ capture, as well as application of captured $CO_2$ in food-grade usage.

# PROPOSED WORK

TRL advancement of Avnos' technology is accomplished via a series of numerous projects of progressive scale and complexity, outlined as follows:

| Commercial Development Timeline | | | |
|---|---|---|---|
| Project: | Operations: | Development Objective: | Project Objective: |
| DoE Project<br>30 TPA<br>Bakersfield CA | 2023 | Initial demonstration of moisture-swing technology for carbon capture in open atmospheric conditions | 30 TPA demonstration facility |
| ONR Project<br>(600 TPA)<br>Bridgewater, NJ | Q2 - 2025 | Demonstration of contactor performance for moisture swing $CO_2$ capture and humidity management using enthalpy wheel; demonstrate low energy approach at scale. This ONR Project represents a single modular unit that is then repeated for larger scale projects below – demonstrated core technology at 'scale up' sizes and integration | Scaled demonstration of a unit (enthalpy wheel, vacuum chamber, AWE, MSA, configuration) |
| Large Scale DAC Deployment – FEL Studies<br>(>10,000 TPA) | 2027 | Selection of latest generation of $CO_2$ capture materials tailored for site specific conditions to progress engineering design | Finalization of engineering design parameters for large scale project deployment |
| Large Scale DAC Deployment<br>(>10,000 TPA) | 2027 | Realization of economies of scale and technology optimization with respect to engineering and design. Supply chain development for efficient procurement | Large scale commercial deployment |

The Key Performance Attributes noted below are developed from laboratory and DOE pilot plant-based experiments/data, process models and standard engineering calculations. Performance requirements are informed by Avnos' internal technology roadmap for system scaling.

- Total Thermal Energy Requirement: N/A
- Energy Source: Electricity

Achievement of a TRL 9 was assumed for the Western Regional DAC Hub study based on deployment and operation of another similarly scaled project.

# POST-PROJECT PLANS

Achievement of plant operation on the scale of the Western Regional DAC hub would be a significant milestone for Avnos, as it would demonstrate, at a significant scale, the efficacy and maturity (TRL 9) of our HDAC technology. The subsequent aim of technology deployment will be the realization of economies of scale through larger projects premised on a modularized multi-copy of the smaller scale cluster model.

## Appendix A.3 – Sustaera Description and Technology Maturation Plan

# DAC TECHNOLOGY DESCRIPTION and TECHNOLOGY MATURATION PLAN

**Sustaera**

## DE-FE0032379

## Western Regional DAC Hub

**SUBMITTED TO**

U.S. Department of Energy

Office of Fossil Energy and Carbon Management (FECM)

# A. DAC PROCESS DESCRIPTION

## A.1. Overall Process Description

The Sustaera DAC process is simple and modularized. Each unit, known as an air contactor, consists of sub-units each containing a pair of contactor stacks made up of individual adsorption/desorption chambers. The contactor stacks are arranged in two parallel walls, creating a rectangular plot layout, with a fan dedicated to each sub-unit. Each adsorption/desorption chamber hosts multiple structured material assembly (SMA), Sustaera's differentiating technology. The fan in the center of each sub-unit (between two contactor stacks) of the air contactor moves air through the SMA within each chamber under atmospheric temperature and pressure after filtering of particles where the sorbent absorbs the $CO_2$ selectively, sending $CO_2$ lean air back to the atmosphere. Next, the chambers are sealed from ambient air and subjected to a mild vacuum to remove air components for higher purity $CO_2$ and then the SMA are heated directly via integrated electric resistive heating to release the $CO_2$ from the sorbent, which is collected and conditioned by removing water to be sequestered permanently out of the atmosphere. Upon completion of desorption, cooling of the SMA is achieved via flowing air through the monoliths during the adsorption step, thus negating the need for a complex and expensive cooling mechanism. Each chamber of SMA modules undergoes a batch process cycle of adsorption, air evacuation, and desorption steps approximately once every 30 minutes to 1 hour, depending on the atmospheric conditions. The chambers are then arranged in a process cycle to produce a continuous flow of crude $CO_2$ product to the downstream purification (in DAC Hub BOP scope) which purifies the $CO_2$ product to sequestration specification.

# B. TECHNOLOGY READINESS LEVEL

## B.1. Current Technology Readiness Level (TRL) of the Proposed Technology

TRL - 5

## B.2. Description of Prior Research

Sustaera has developed a conductive structured sorbent system. Initial research conducted on sorbent capacity and stability in lab scale test reactors. Proven stability of sorbent in DAC conditions with adsorption gas of 21% $O_2$ 400ppmv $CO_2$ in $N_2$ at 67% RH and direct air cooling of structured sorbent after desorption (80-100C) over 2,000 cycles. In parallel, materials and processes to create the electrically conductive structure were developed and then tested in lab and bench scale test reactors. Demonstrated stability and uniform heating of the resistive structured system with robust electrical connections over 1,000 cycles. The sorbent and conductive elements were integrated into a conductive structured sorbent system and tested in 1 tonne per year (TPY) bench scale unit. This unit utilizes outdoor untreated ambient air during adsorption and integrated electric resistive heating for regeneration. The 1 TPY unit is fully automated and includes all sub-system and equipment (i.e. blowers, vacuum pumps, valves, analyzers, and instruments) that would be utilized in a commercial system.

To date, the 1 TPY unit has operated continuously for 28 days providing results to validate current techno-economic analysis (TEA) assumptions. The results of testing revealed highly stable and performing sorbent with effective/efficient electrical resistive regeneration. Furthermore, the 1 TPY unit established baseline for design basis of future scaled up units. Modular design of technology and engineered components enable predictable scalability of $CO_2$ Capture performance.

### B.3. Target Commercial Applications

Sustaera's current commercial application is primarily in carbon removal via geologic sequestration. However, there are some minor $CO_2$ utilization opportunities being explored in the biological, food/beverage, and water treatment sectors. Sustaera intends to enter the market as a DAC equipment and technology license supplier to carbon removal sequestration project developers.

## C. PROPOSED WORK

### C.1. Current Project Work to Mature Technology

Sustaera's core technology is a conductive structured sorbent system utilizing existing low mass ceramic substrates (honeycomb monolith). The ceramic substrate was selected because it allows acceptable pressure drop during adsorption and low mass resulting in low specific energy to remove $CO_2$. Also, it provides high geometric surface area per unit volume to enable maximum $CO_2$ volumetric productivity. The substrate is made electrically conductive through materials coating and thermal processing steps. Additionally, the substrate is coated with sorbent material. The final integrated substrate structure is installed in a module system, which serves as the building block for our engineered solution.

The module is inserted into a chamber that can be isolated during desorption. Multiple chambers are combined to form a unit to achieve optimal adsorption to desorption cycle time ratio for continuous $CO_2$ capture. A large fan provides air movement through the chamber when not isolated during adsorption step. A vacuum pump removes desorbed gases when the chambers are isolated, and power is applied for regeneration. Finally, $CO_2$ is separated from co-adsorbed water to be sequestered. All components are off the shelf and readily available for integration.

**Table 1.** ***How Proposed Work Relates to Technology Maturation***

| Key Technology Component | Current TRL | Component's Role |
|---|---|---|
| **Conductive structured sorbent system module** | 5 | Mechanical frame to support structure sorbent and electrical connections for efficient and uniform heating |
| **Air contactor chamber & isolation** | 5 | Holds module for efficient air contacting during adsorption and provides isolation from air to pull vacuum during desorption |
| **Water knockout equipment** | 9 | Condense and separate water from $CO_2$ product stream |
| **Control loop of desorption heating circuit** | 9 | Currently utilize expensive fiber optics to measure temperature and provide feedback to power modulation system |
| **Predictive modeling of performance** | 5 | Model enables determination of $CO_2$ capture efficiency based on climatic data and power availability |

## C.2. Current and Required Performance

To advance technology from current TRL of 5 (1 TPY), Sustaera intends to reduce capital expenditures (CAPEX) intensity, specific energy, and operations and maintenance (O&M) costs. This will be achieved by:

- Reduction of CAPEX Intensity – improved air contactor design by significant increase of surface area utilization and increasing scale of module will ensure better economics on a per unit basis. For example, Sustaera is currently purchasing single digit conductive structured sorbent produced on an research and development (R&D) pilot line. In the proposed hub, the conductive structured sorbent will be produced on automated commercial manufacturing line, thereby significantly reducing unit cost. Furthermore, economies of scale will reduce the auxiliary equipment count and cost, instrumentation/valves count and costs, and isolation contactor manufacturing unit cost.
- Reduction of Specific Energy – by reducing thermal mass and increasing volumetric productivity of the conductive structured sorbent. Also, by optimizing equipment count and sizing to ensure maximum utilization. Selection of equipment based on specific DAC Hub site conditions will improve energy utilization efficiency. Reduction of void and increasing ratio of conductive structured sorbent to isolation contactor volume lowers heat losses, thereby improving specific energy.
- Reduction of O&M Costs – current bench scale unit is highly instrumented for research purposes, which will not be required in the proposed hub. Additionally, bench scale equipment has reduced availability compared to commercial equipment planned for the proposed hub. Due to the research nature of the bench scale unit, additional operator intervention is required than the proposed hub system. The proposed hub equipment will be automated to function with minimal operator involvement.

**Table 2.** ***Current and Required Performance***

| Performance Attribute | Current Performance | Required Performance | Explanation |
|---|---|---|---|
| **CAPEX Intensity** | Greater than \$10,000/tonne -year | Under \$1,000/tonne -year | Sustaera has a robust TEA that includes detailed costs for manufacturing, construction, commissioning and operation costs (including RAM analysis). The TEA is used to make capital vs. Operational optimization decisions based on the final unit costs. The capital costs are supported with vendor and contractor costs. |
| **Specific Energy** | Greater than 25 GJ/tonne $CO_2$ | Under 5.5 GJ/tonne $CO_2$ | The Sustaera TEA specific energy calculation procedure has been validated by empirical testing in bench scale unit. The forecasted specific energy is based on targeted unit performance with increasing scale providing Sustaera guidance on improvement areas such thermal mass and volumetric productivity. |
| **O&M Costs** | Greater than \$100/tonne $CO_2$ | Under \$10/tonne $CO_2$ | Sustaera performed a bottom-up O&M cost including operators, spare, and maintenance schedule for the proposed hub. |

# D. POST-PROJECT PLANS

## D.1. Future Project Work to Mature Technology

With the proposed work on components of our technology (Table 1) we intend to identify the key components on unit cost and unit performance via engineering study and cost estimate efforts. Once these are identified, we can prioritize testing and further development work of these components outside of the study with the planned future project work identified in Table 3, including Pilot testing and initial scale-up to 2,500 TPY removal. Testing and further development of these key components will aid/help in refining the cost and performance estimates to improve confidence in achieving unit cost and performance targets in operation.

Next planned testing of components is a pilot unit to demonstrate scale-up of conductive structured sorbent system from Lab Demo (TRL 5) to Pilot (TRL 6) as well as key components such as an air contactor. Sustaera is exploring funding and siting options for demonstrating the conductive structured sorbent system in a Pilot.

Next proposed testing is a minimum 2,500 TPY commercial facility demonstrating $CO_2$ removal from conductive structured sorbent system integration with improved DAC contactor and $CO_2$ processing equipment identified in this work.

**Table 3.** ***Future Work to Mature Technology***

| Key Technology Component | Target TRL at End of Study | Future Target TRL |
|---|---|---|
| **Conductive Structured Sorbent System** | 5 | 6 |
| **Improvements to Air Contactor** | 5 | 7 |

## D.2. Go-to-Market and Deployment Strategy

Upon completion of the technology development to TRL 7 as laid out above, Sustaera intends to enter the carbon removal market as a DAC Technology provider, offering our conductive structure sorbent systems and the associated air contacting equipment and $CO_2$ processing equipment as well as an operating license and control system. We envision working with project developers and/or $CO_2$ sequestration/storage developers to sell our equipment into the carbon removal project which is operated by the site owner, responsible for renewable energy and other utility supplies. We intend to have a phased deployment approach to manage technical and engineering risks while balancing capital requirements to prove the unit cost and performance in steps. After technology development up to ~2,500 TPY scale, Sustaera is planning on building a 75,000 TPY facility followed by ~250,000 to 500,000 TPY facility and finally the full-scale 1MMTPY facility meant to be a Nth of a Kind (NOAK) repeatable deployment. This pragmatic approach allows Sustaera to manage deployment against uncertain and developing market demand as well as continued growth in renewable power supply.

## Appendix B – Initial DAC Hub Balance of Plant Design Concept

# PHASE 0A FINAL REPORT

## Western Regional Direct Air Capture (DAC) Hub Study Project

**PREPARED FOR**

Chevron

Chevron New Energies

# Introduction

The Department of Energy contracted with Chevron New Energies, a division of Chevron U.S.A. Inc. (Recipient), to explore the feasibility of a potential Direct Air Capture (DAC) Hub in Kern County, California. The study completed pre-feasibility.

The study considered an Initial Plant Capacity of 50,000 net tonnes per annum of $CO_2$ removal from the atmosphere (per DAC technology) and a Final Plant Capacity of 1,000,000 net tonnes per annum of $CO_2$ removal.

Three DAC Technology Providers (280 Earth, Avnos, and Sustaera) developed designs for their respective DAC Islands. Black & Veatch served as Project Integrator and Balance of Plant Designer.

# Definitions

## Acronyms

**Table 1 Report acronyms**

| Term | Definition |
|---|---|
| BOP | Balance of Plant |
| DAC | Direct Air Capture |
| KTA | Thousand Tonnes per Annum |
| MTA | Million Tonnes per Annum |

# Initial DAC Hub Balance of Plant Design Concept

The subsections below describe the design criteria utilized for the design of the initial hub capacity as well as the final hub capacity. Where additional design criteria unique to the final hub capacity was required, it is noted below.

## Basis of Design

At the start of the study, a specific site had not been selected. Consequently, hub ambient conditions were based on data for Meadows Field, CA as a representation of the expected hub location.

## Ambient Conditions

**Table 2 Design Temperatures, Pressure, Relative Humidity**

| Parameter | Value |
|---|---|
| Atmosphere | Inland |
| Weather Station | Meadows Field, CA (WMO: 723840) |
| Maximum Temperature for Mechanical Properties | 115°F |
| Minimum Temperature for Mechanical Properties | 20.5°F |
| Summer Process Design Temperature (Wet Bulb)[1] | 73.5 °F |
| Design Relative Humidity (Coincident with summer wet bulb design temperature) | 32.3 |
| Summer Process Design Temperature (Dry Bulb)[1] | 103.4 °F |
| Design Relative Humidity (Coincident with summer dry bulb design temperature) | 18 |
| Winter Process Design Temperature (Dry Bulb)[3] | 38°F |
| Winter Process Design Wet Bulb Temperature (Coincident with winter dry bulb design temperature) [3] | 34.6°F |
| Winter Process Design Relative Humidity (Coincident with winter dry bulb design temperature) [3] | 72.1 |
| Winter Freeze Protection Temperature (Dry Bulb) [2] | 29.2°F |
| Annual Average Dry Bulb | 66.2 °F |
| Annual Average Mean Coincident Wet Bulb | 52.7 °F |
| Annual Average Mean Coincident Relative Humidity | 40 |

NOTES:

1. Process summer design temperatures based on 2021 ASHRAE data for July 2% exceedance value for the Meadows Field, California weather station.
2. Process winter design temperatures based on 2021 ASHRAE data for Mean Min Extreme Annual Temperature for the Meadows Field, California weather station.
3. Assumed margin above freezing, limiting hours below winter design dry bulb temperature to <0.5% a year.

## BOP Design Concept

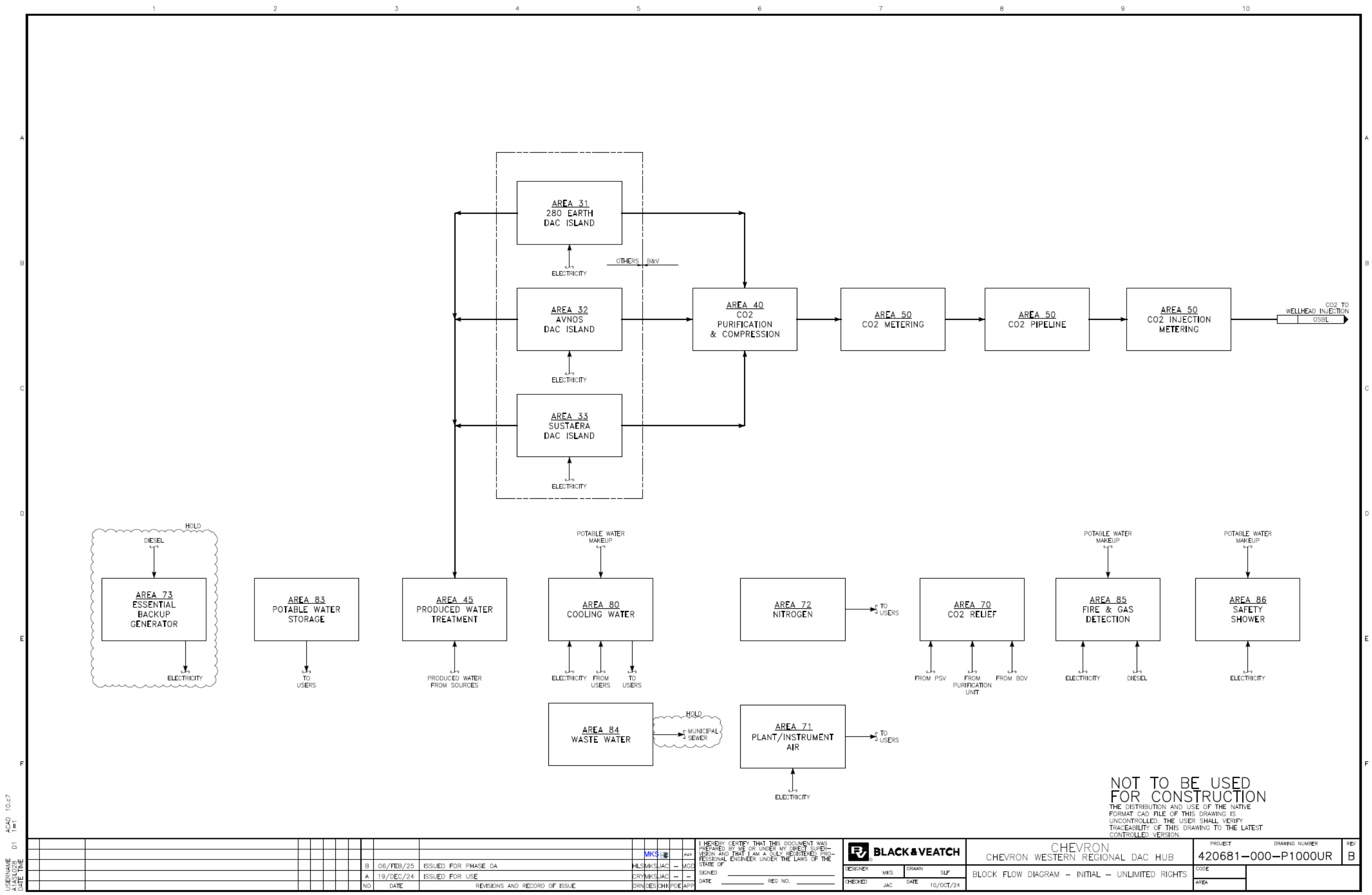
### General Requirements

The integrated DAC hub site consisted of 3 DAC technology islands to capture $CO_2$ with a Balance of Plant (BOP) support facility to supply utilities, treat water, and provide final product compression and treatment. The BOP was designed by Black & Veatch to receive captured $CO_2$ piped to its boundary limits via separate flanges from the 3 DAC technology providers. The captured $CO_2$ was assumed to be compressed and conditioned in the BOP before entering a pipeline for transport to the project's sequestration wells. The utility support included within the BOP included plant and instrument air, nitrogen, and water handling/treatment (as each DAC technology is a net water producer). In addition, the BOP contained the interfaces for power generation/distribution, plant water, and other external project interfaces.

### $CO_2$ Product

$CO_2$ from each provider would be collected, purified, and compressed to meet typical $CO_2$ purity requirements for transfer to an injection well.

## Appendix B.1 – Block Flow Diagram


AREA 31
280 EARTH
DAC ISLAND
AREA 32
AVNOS
DAC ISLAND
AREA 33
SUSTAERA
DAC ISLAND
ELECTRICITY
OTHERS
B&V
AREA 40
CO2
PURIFICATION
& COMPRESSION
AREA 50
CO2 METERING
AREA 50
CO2 PIPELINE
AREA 50
CO2 INJECTION
METERING
CO2 TO
WELLHEAD INJECTION
OSBL
HOLD
DIESEL
AREA 73
ESSENTIAL
BACKUP
GENERATOR
AREA 83
POTABLE WATER
STORAGE
TO
USERS
AREA 45
PRODUCED WATER
TREATMENT
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USERS
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MUNICIPAL
SEWER
AREA 71
PLANT/INSTRUMENT
AIR
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## Appendix C – Preliminary LCA

## LCA Methods

*Goal and Scope*

A life cycle greenhouse gas assessment was conducted to estimate the carbon intensity of carbon dioxide capture and storage, as measured by kg $CO_2$-equivalent per kg of captured from air and permanently stored carbon dioxide (kg $CO_2e$/kg $CO_2$). The purpose of this preliminary life cycle assessment (pre-LCA) was to estimate the net effectiveness of a direct air capture (DAC) hub located in Kern County, CA. The site was presumed to house three DAC technologies, including 280 Earth, Avnos, and Sustaera, along with the associated Balance of Plant (BOP) developed by Black & Veatch. The scope of this pre-LCA was from cradle-to-$CO_2$ storage in a geologic repository. Processes and inputs were provided by the respective parties, including the DAC technologies and Black & Veatch.

## Life Cycle Inventory

The life cycle inventory requires two types of data: data for the foreground system, which consists of direct inputs and outputs of the DAC hub, and data for the background systems which provide the upstream energy, raw materials, and emissions that occur throughout the supply chains of the materials, energy and services used within the DAC hub.

Foreground data were supplied by Black & Veatch for each of the three DAC technologies, as well as site-wide utility requirements and other BOP systems.

Reference LCI datasets were drawn from a variety of sources, including reference LCI databases and peer-reviewed scholarly journal articles.

These datasets were mostly from the correct region (California, US West, or US). The datasets that were not regionally appropriate were used due to the absence of available data and were not expected to contribute significantly to uncertainty in model outcomes.

*Impact assessment*

Impact assessment only includes the global warming category, since this preliminary LCA is restricted to greenhouse gas emissions. IPCC AR6 100-year global warming potential values (including biogenic but excluding climate-carbon feedbacks) were used to convert GHG flows in the reference LCIs to $CO_2e$ flows (IPCC, 2021).

## References

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

## Appendix D – DAC Hub Data Table

| Units | Units | Initial Capacity | Final Capacity (if applicable)[2] |
|---|---|---|---|
| **Scalability and DAC Technologies** | | | |
| DAC Hub Proposed Scale (Net $CO_2$ captured from the atmosphere) | Net tonne $CO_2$/yr. | 150,000 target capacity | 1,000,000 target capacity |
| DAC Hub Proposed Scale (Gross $CO_2$ captured from the atmosphere) | Gross tonne $CO_2$/yr. | Due to multiple factors, driven largely by the carbon intensity of potential energy sources, hub life cycle impacts may range from an additional 10% to over 100% of $CO_2$ stored | Due to multiple factors, driven largely by the carbon intensity of potential energy sources, hub life cycle impacts may range from an additional 10% to over 100% of $CO_2$ stored |
| DAC Technology(ies) in DAC Hub and TRL[1] | Technology and TRL | 280 Earth – 7<br>Avnos – 6<br>Sustaera – 5 | 280 Earth – 7<br>Avnos – 6<br>Sustaera – 5 |
| **Carbon Potential** | | | |
| $CO_2$ Conversion Offtakers Available | - | NA | NA |
| $CO_2$ Conversion Capacity for DAC Hub | tonne $CO_2$/yr. | NA | NA |
| $CO_2$ Storage Options for DAC Hub | - | Geologic storage | Geologic storage |
| $CO_2$ Storage Capacity Available[3] | tonne $CO_2$ | ≥ 1.8 million | ≥ 12 million |
| **Resources** | | | |
| $CO_2$ Storage Infrastructure Available | - | No pre-existing infrastructure | No pre-existing infrastructure |
| $CO_2$ Transport Infrastructure Available | - | No pre-existing infrastructure | No pre-existing infrastructure |
| $CO_2$ Pipeline needed for DAC Hub | miles | Less than 10 miles | Less than 10 miles |
| Total Land Requirements for DAC Hub | $m^2$ | 120,000 – 200,000[5] | 600,000 – 1,000,000[5] |
| Total Water Requirements for DAC Hub | tonnes/yr. | DAC processes are net water producing[6] | DAC processes are net water producing[6] |
| Energy Sources Available | type | Electric | Electric |

| | | | |
|---|---|---|---|
| Renewable and Low Carbon Energy Available[4] | type | Renewable and lower carbon energy available via grid | Renewable and lower carbon energy available via grid |
| Total Energy Requirements for DAC Hub | GJ/tonne $CO_2$ removed from atmosphere | 6 – 14 | 6 – 14 |
| Total Thermal Energy Requirements for DAC Hub | GJ/tonne $CO_2$ removed from atmosphere | | |
| Total Electrical Energy Requirements for DAC Hub | GJ/tonne $CO_2$ removed from atmosphere | | |
| **Emissions** | | | |
| Type of Emission related to Energy Source | Type (e.g. natural gas leakage, $CO_2$, etc.) | $CO_2$e as assessed in the pre-LCA | $CO_2$e as assessed in the pre-LCA |
| Total Emissions related to Energy Source | $CO_2$e tonne/yr. | Due to multiple factors, driven largely by the carbon intensity of potential energy sources, hub life cycle impacts may range from an additional 10% to over 100% of $CO_2$ stored | Due to multiple factors, driven largely by the carbon intensity of potential energy sources, hub life cycle impacts may range from an additional 10% to over 100% of $CO_2$ stored |
| **Geographic Diversity - DAC Hub Region** | | | |
| DAC Hub Area | Square miles | | |
| DAC Hub Region States | State(s) | California | California |
| DAC Hub Region counties | counties | Kern | Kern |
| DAC Hub Region cities | Cities | | |
| DAC Hub Region zip codes | Zip codes | | |
| **Hubs in Fossil-Producing Regions[7]** | | | |
| Coal production (current) in DAC Hub Region | Tonnes/yr. | NA | NA |
| Coal Production (Retired last 10 years) in DAC Hub Region | Tonnes/yr. | NA | NA |
| Oil Production (current) in DAC Hub Region | Thousand Barrels per Day | 324[8] | 324[8] |
| Oil Production (Retired last 10 years) in DAC Hub Region | Thousand Barrels per Day | 221[8] | 221[8] |
| Gas Production (current) in DAC Hub Region | Billion Cubic meters per year | 3.54[9] | 3.54[9] |

| | | | |
|---|---|---|---|
| Gas Production (Retired last 10 years) in DAC Hub Region | Billion Cubic meters per year | 2.77[9] | 2.77[9] |
| **Carbon Intensity of Local Industry[7]** | | | |
| Carbon Intensity of Local Industry | Kg $CO_2$/million BTU | 51.4[10] | 51.4[10] |
| Retired Carbon-Intensive Industrial Capacity | - | 5-15% reduction[11, 12] | 5-15% reduction[11, 12] |
| **Economic Distressed Area** | | | |
| Economic Distressed Area(s) in DAC Hub Region | Yes/No | Yes | Yes |
| **Employment** | | | |
| Employment Potential | Jobs (operating-full time) | 25-75 (initial estimates) | 100 – 150 (initial estimates) |
| Employment Potential | Jobs (construction) | TBD | TBD |

[1] List all the DAC technologies proposed in the DAC Hub and their current TRL.
[2] Certain pre-feasibility activities were limited to the initial hub capacity design, such as the preliminary LCA. Estimates for the final hub capacity build-out generally assume a proportional scale up of the initial hub capacity design concept.
[3] $CO_2$ Storage Capacity does not imply storage volumes in accordance with SPE $CO_2$ Storage Resource Management System (SRMS) definitions of capacity.
[4] List the renewable and low carbon energy available in the proposed DAC Hub region, such as wind, solar, geothermal, nuclear, and fossil fuel or biomass equipped with CCUS.
[5] Estimates for DAC and BOP systems, excluding land requirements for primary energy supply and generation infrastructure.
[6] Imported water is expected to be limited to intermittent users such as eyewash stations, potable water, etc.
[7] Based on publicly available data.
[8] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mcrfpca1&f=a
[9] https://www.eia.gov/petroleum/wells/
[10] https://www.eia.gov/environment/emissions/state/analysis/pdf/table8.pdf
[11] https://www.eia.gov/state/seds/sep_use/ind/pdf/use_ind_CA.pdf
[12] https://ww2.arb.ca.gov/sites/default/files/2024-09/nc-2000_2022_ghg_inventory_trends.pdf

## Appendix E – Storage Field Development Plan

### Executive Summary

Recipient identified Kern County, California as a potential location for the Western Regional Direct Air Capture (DAC) Hub from which to complete the pre-feasibility study to capture, transport, and permanently store $CO_2$.

The Vedder Formation is a saline aquifer located within the San Joaquin Basin. This formation has been highlighted by the Lawrence Livermore National Labs as a key sequestration interval in the state of California with 0.9-3.6 billion tons of $CO_2$ storage capacity in the eastern San Joaquin Basin alone (Baker et. Al, 2020). Recipient has significant rights to the Vedder Formation that are expected to exceed the minimum storage requirements of 12 years of operation. Due to the early nature of this pre-feasibility study, the pore space discussed in this plan is not allocated to the Western Regional DAC Hub concept.

This Storage Field Development Plan update has been developed in parallel to the funded DOE scopes as independent work not funded under this study.

### References

Baker, S.E., Joshuah K. Stolaroff, George Peridas, Simon H. Pang, Hannah M. Goldstein, Felicia R. Lucci, Wenqin Li, Eric W. Slessarev, Jennifer Pett-Ridge, Frederick J. Ryerson, Jeff L. Wagoner, Whitney Kirkendall, Roger D. Aines, Daniel L. Sanchez, Bodie Cabiyo, Joffre Baker, Sean McCoy, Sam Uden, Ron Runnebaum, Jennifer Wilcox, Peter C. Psarras, Hélène Pilorgé, Noah McQueen, Daniel Maynard, Colin McCormick, 2020, Getting to Neutral: Options for Negative Carbon Emissions in California, January 2020, Lawrence Livermore National Laboratory, LLNL-TR-796100. https://gs.llnl.gov/sites/gs/files/2021-08/getting_to_neutral.pdf