

DIRECT AIR CAPTURE RECOVERY OF ENERGY FOR CCUS PARTNERSHIP (DAC RECO₂UP)

Federal Agency:	U.S. Department of Energy/NETL
Federal Number:	DE-FE0031961
Project Title:	DIRECT AIR CAPTURE RECOVERY OF ENERGY FOR CCUS PARTNERSHIP (DAC RECO ₂ UP)
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Report Type:	Final Progress Report
Reporting Period Start Date:	October 1, 2020
Reporting Period End Date:	September 30, 2024
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Submission Date:	12/20/2024

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Abstract

The “Direct Air Capture Recovery of Energy for CCUS Partnership (DAC RECO₂UP)” project employs a team approach and supports the U.S. Department of Energy Office of Fossil Energy and Carbon Management’s (DOE-FECM) goal to decrease the cost of capture through the testing of existing direct air capture (DAC) materials in integrated field units that produce a concentrated carbon dioxide (CO₂) stream of at least 95% purity. Solid-amine CO₂ adsorption-desorption contactor technology, proven in the laboratory, is undergoing high-fidelity design/validation. Recoverable energy is readily available from a large number of commercial locations where DAC can be deployed; therefore, advancing the fidelity of energy recovery to directly reduce the cost of DAC is a key project objective. In addition, many commercial facilities have low-concentration CO₂ vents that are uneconomical to treat alone but could provide more efficient mass and thermal transport to DAC systems with integrated energy recovery and flexible CO₂ treatment capabilities. Technology scale-up leverages past research and occurs in a commercially relevant environment at the National Carbon Capture Center. Pre-screening techno-economic analysis, risk assessments, and life cycle analysis are being performed by experienced team members. Results of the project will address critical technical barriers that, when solved, will improve the capital and operating costs of DAC while validating commercial relevance of cost and product quality/need.

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Executive Summary

In early 2021, the Southern States Energy Board (SSEB) launched a project known as the Direct Air Capture Recovery of Energy for CCUS Partnership (DAC RECO₂UP). The project met or exceeded all metrics and successfully concluded on July 31, 2024.

The project team consists of SSEB, Aircapture (AC), Amy Landis, Ph. D., at Colorado School of Mines (Mines), Synapse Development Group (Synapse), Global Thermostat (GT), Crescent Resource Innovation (CRI), and Southern Company Services (SCS). This work was completed in cooperation with the U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL) and the NCCC.

The DAC RECO₂UP project was the first direct air capture (DAC) system installed at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama. The NCCC provided a commercially relevant environment in which to assess the DAC solid-amine CO₂ adsorption-desorption contactor technology. Five testing campaigns were completed with an experimental period of over 3,300 hours, allowing the project team to obtain a sizable and varied database. The in-field operational data was used to develop a pre-screening Techno-Economic Analysis (TEA), Life Cycle Analysis (LCA) and assess risk. Additionally, these findings allowed the team to rapidly advance from an initial system Serial Number 1 (SN-1) to an improved system Serial Number 3 (SN-3). Eight DAC units designed from the lessons learned within the DAC RECO₂UP project are being currently deployed internationally for commercial installation in the United Arab Emirates and were the basis for the AC portion of the SEDAC Hub project (DE-FE0032392).

The DAC RECO₂UP project supports the DOE FECM's goal to decrease the cost of CO₂ capture through the testing of existing DAC materials in integrated field units that produce a concentrated CO₂ stream of at least 95% purity.

Recoverable energy is readily available from many commercial locations where DAC can be deployed; therefore, advancing the fidelity of energy recovery to directly reduce the cost of DAC was a key project objective. In addition, many commercial facilities have low-concentration CO₂ vents that are uneconomical to treat alone but could provide more efficient mass and thermal transport to DAC systems with integrated energy recovery and flexible CO₂ treatment capabilities.

Results of the project addressed critical technical barriers and demonstrated improved capital and operating costs of DAC technology while validating commercial relevance of cost and product quality/need. Project Hajar, a commercial project in the UAE utilizing AC's DAC technology to mineralize CO₂, utilizes the lessons learned from DAC RECO₂UP.

This Report Focuses on the efforts and results accomplished leading up to and during the testing phase at the NCCC covering the period from October 2022 through July 2024.

Results and Discussion

Task 1.0 – Project Management and Planning

Subtask 1.1 – Project Management Plan

Management and Oversight Meetings and Field Trips

On February 28, 2023, Dr. Ben Wernette of SSEB and Brian Hill of CRI visited the NCCC in Wilsonville, Alabama, to meet with John Carroll of Southern Company. The visit's purpose was to discuss the status of the DAC test skid installation into the bay at the NCCC. The meeting included a site visit to the NCCC bay to observe the DAC test skid. While at the test bay, Andy Mosely, from AC joined the group and provided an overview of the installed DAC skid. Installation was on hold as the team was reworking non-compliant electrical cables. The original cables were not rated for exterior application. The team replaced the cables with exterior grade cables to meet Alabama code.

On May 16, 2023, Patricia Berry, Senior Geologist, SSEB, traveled to the NCCC to conduct a site visit and meet with Naomi O’Neil, NETL Program Manager.

On June 7-9, 2023, Matt Atwood and Andy Mosely of AC conducted a NETL peer review site visit and technology workshop at the NCCC around the AC DAC system and technology (Figure 1).



Figure 1 – NETL Peer Review site visit and technology workshop at NCCC, June 7-9, 2023. Photo courtesy of the NCCC.

On August 29, 2023, Patricia Berry of SSEB and Joshua Miles, Chris Wheeler, and Andy Louwagie of AC met in Pittsburgh, Pennsylvania, to discuss recent changes to AC’s staff, the project timeline, status of the unit onsite at the NCCC, upcoming deliverables/milestones, and the potential need for a project No Cost Time Extension.

On November 3, 2023, SSEB hosted an Open House for its “Optimizing Alabama’s CO₂ Storage in Shelby County (Project OASIS)” CarbonSAFE Phase II project, DE-FE0032267. The meeting offered SSEB’s Dr. Ben Wernette the opportunity for Subrecipient monitoring of the DAC RECO₂UP testing operations. The Project OASIS Open House agenda and itinerary included: (1) an educational presentation on CO₂ capture technologies; (2) an overview of Southern Company’s CO₂ storage research program; (3) SSEB’s Carbon Management Program, including the Project OASIS and DAC RECO₂UP projects; (4) a tour of the NCCC, including the DAC RECO₂UP skids and testing area; and (5) a tour of the Project OASIS drilling site. Participants included over 30 individuals representing Advanced Resources International, Inc., Alabama A&M University, Alabama Oil and Gas Board, Alabama Power, Argos, Auburn University, Carbon America, Carmeuse, Google, Lhoist, Pure Sky, Southern Company, and SSEB.

On November 7-8, 2023, Matt Atwood, Michael Vyvoda and Andy Mosely of AC hosted a Technology Deep Dive, including a site walk through and Technology Overview at the NCCC around the AC DAC technology (Figure 2).



Figure 2 – AC hosted a Technology Deep Dive at the NCCC on November 7-8, 2024. Photo courtesy of the NCCC.

On March 20, 2024, SSEB’s Dr. Nicholas Kaylor and CRI’s Brian Hill visited the NCCC as part of an external activity and performed DAC RECO₂UP Subrecipient and test center monitoring while on site.



Figure 3 – SSEB's Project OASIS community benefits engagement activity included a tour of the DAC RECO₂UP test site as part of the event, April 19, 2024. Photo courtesy of the NCCC.

On April 19, 2024, SSEB's Dr. Ben Wernette visited the NCCC as part of a Project OASIS Community Benefits activity and performed DAC RECO₂UP Subrecipient and test center monitoring while on site (Figure 3). The event supported engagement and skills development for Alabama A&M University students and included a broad overview of carbon capture and storage, as well as a general update on the status of Project OASIS. Participants met with Plant Gaston staff and toured the NCCC and the DAC RECO₂UP test site as part of this event.

Foreign National Participation

Foreign National participation was requested and processed pursuant to the Terms and Conditions of the Award. During the Period of Performance, two individuals were approved. Marek Myszkowski, Synapse, was approved on February 2, 2021, for off-site award work for the period of February 5, 2021, through September 30, 2023. Svenja Telle, AC, was approved on July 27, 2022, for off-site award work for the period of July 20, 2022, through January 31, 2024.

Project Schedule

The Gantt chart provided below in Figure 4 represents the final schedule for the DAC RECO₂UP project.

Supply Chain Disruptions

Although most project activities remained on schedule, the ordering of certain parts to build the DAC machine and supporting skids progressed at a slower pace than planned due to impacts from the Covid pandemic, and the expected delivery time for certain parts was lengthened due to unprecedented supply chain disruptions. Ordering took longer as AC sought alternative sources of component parts and spent substantial time with prospective suppliers working on solutions to the long lead times for selected parts. For instance, the longest lead item, the fan, initially had a lead time of several weeks that extended to twenty weeks in less than three months. To mitigate this issue, AC prioritized ordering by longest lead time parts first and fabricating some parts instead of ordering them from suppliers.

Project Deliverables – Statement of Project Objectives

In addition to the periodic and final reports required by the Federal Assistance Reporting Checklist (FARC), the SOPO presented a table of task-specific project deliverables that documented progress toward, and completion of, the scope of work (SOW) outlined in the SOPO. As of July 31, 2024, all project deliverables were completed, submitted in accordance with the prevailing version of the SOPO as noted in Table 1.

Table 1 - DAC RECO₂UP Deliverables

Task	Deliverables	Planned Completion Date	Revised Completion Date	Actual Completion Date
1.1.a	Project Management Plan	3/18/21		2/17/21
1.2.a	Technology Maturation Plan	5/17/21		9/28/21
1.2.b	Technology Maturation Plan	1/1/24	7/31/24	7/31/24
1.3.a	NCCC Technology Collaboration Agreement and Other Access Agreements/Documents	10/31/22		10/31/22
2.2.a	Preliminary Technology EH&S Risk Assessment	6/16/21		10/14/21
2.2.b	Technology EH&S Assessment Update, Post-Field Testing	11/2/23	7/31/24	7/31/24
2.3.a	Pre-Operational Risk Management and HAZOP Report	1/4/23	5/8/23	5/17/23
3.2.a	Integrated System Process & Heat Model	10/1/21		10/5/21
4.3.a	Commissioning Report & Test Matrix	10/31/22		10/31/22
5.1.a	Site Commissioning Report & Final Operational Plan	2/2/23	2/24/23	2/7/23 & 5/12/23
6.1.a	Updated State Point Data Table	1/1/24	7/31/24	7/31/24
6.1.b	Pre-screening Techno-Economic Analysis	1/1/24	7/31/24	7/31/24
6.1.c	Pre-screening Life Cycle Analysis	1/1/24	7/31/24	7/31/24

Project Milestones – Project Management Plan

In addition to the periodic and final reports required by the FARC and SOPO, the Project Management Plan (PMP) sets a list of project milestones. Some milestones were task-based, while others were

quantitative, and indicated progress toward accomplishing the project goals. Progress was also reported as part of the required Research Performance Progress Reports (RPPR). As of July 31, 2024, all project milestones were achieved and verification documentation submitted in accordance with the prevailing version of the PMP as reflected in Table 2.

Table 2 - DAC RECO₂UP Milestones

Task	Milestones	Planned Completion Date	Revised Completion Date	Actual Completion Date
1.3.a	Participate in NETL Kickoff Meeting	5/17/21		4/16/21
1.3.b	Fully Executed NCCC Technology Collaboration Agreement and Other Access Agreements/Documents	10/31/22		10/31/22
2.2.a	Complete Preliminary EH&S Assessment	6/16/21		10/14/21
3.1.a	Complete Design and Cost Basis	9/30/21		9/30/21
4.1.a	Initiate Construction of Skids	2/15/22		2/15/22
4.1.b	Finish Construction of Skids	7/31/22		7/31/22
4.3.a	Finish Phase II Commissioning Report and Test Matrix (Testing Data & Model Update)	10/31/22		10/31/22
5.1.a	Skids Transported to NCCC	1/15/23	2/6/23	2/7/23
5.1.b	Complete Site Commissioning at NCCC and Final Operational Plan	2/2/23	5/15/23	5/12/23
5.2.a	Complete DAC Testing at NCCC	11/30/23	7/31/24	7/7/24
5.3.a	Complete Decommissioning and Removal of Skids from Host Site	12/31/23	7/31/24	7/25/24
6.1.a	Complete Pre-screening Techno-Economic Analysis and Life Cycle Analysis	1/1/24	7/31/24	7/31/24

Other NETL Federal Project Manager Document Requests and Webpages

In March 2022, Dr. Duane Miller, Senior Engineer with KeyLogic Systems, an NETL Support Contractor, requested updates to a pre-formatted Carbon Capture Technology Sheet prepared for the DAC RECO₂UP project. AC reviewed the document and incorporated edits. SSEB performed a final edit and returned the document to Dr. Miller in April 2022.

Also in March 2022, SSEB received a data request from the NETL Program Manager, David Lang. The Carbon Capture Program was compiling relevant data from ongoing projects in the program's portfolio to develop a techno-economic and performance-based dashboard that would allow them to perform a quantitative analysis of its project portfolio. AC completed the tables in the document. It was returned to Jacob Weidman and Dave Lang in April 2022.

NETL's Project Landing Page, DAC RECO₂UP

NETL maintains a Project Landing Page for all of its funded projects. The DAC RECO₂UP site can be found here: <https://netl.doe.gov/project-information?p=FE0031961>. The site includes a project description, project benefits, contact information, and a section on presentations, papers, and publications.

Project Technology Sheet, September 2022

In September 2022, NETL published a compendium of carbon capture technologies in their program. A Project Technology Sheet was created and published for the DAC RECO₂UP project and outlined the primary project goal, technical goals, technical content, such as the DAC sorbent process parameters, technology advantages, research and development (R&D) challenges, and project status. The Project Technology Sheet is available via the Project Landing Page or at the direct web link provided here: <https://netl.doe.gov/projects/files/Project%20Technology%20Sheet.pdf>.

Data Management Plan & Intellectual Property Provision

As noted previously, a subtask dedicated to the DMP was eliminated from the SOPO, and the DMP was added as an award attachment. The DAC RECO₂UP DMP was drafted, reviewed, and finalized for the project in January 2021. On January 27, 2021, SSEB and AC staff participated in web meetings with NETL to discuss the requirements and development of the DMP and the IP Provisions to be included in the definitized award. Additional communications with NETL regarding the DMP and IP data listings occurred throughout the remainder of the month. The DMP and IP attachments were included in Award Modification 01, dated February 16, 2021, with an effective date of January 1, 2021.

The DMP explains how data generated during the work performed will be shared and preserved or, when justified, explains why data sharing or preservation is not possible or scientifically appropriate. Three types of data were generated from this project - field data, development data, and desktop data. Unlimited Rights Data and Protected Data were provided in standard formats.

Subtask 1.2 – Technology Maturation Plan

The Project Team developed an initial and final Technology Maturation Plan (TMP) in accordance with the SOPO and its appendices. The TMP describes the initial technology readiness level (TRL) 4 of the proposed technology/technologies, relates the proposed project work to maturation of the proposed technology, describes the expected TRL 5 at the end of the project, and describes any known post-project research and development necessary to further mature the technology.

The initial TMP was submitted on May 18, 2021. On May 20, 2021, NETL requested modifications be made to the TMP. An updated TMP that describes the TRL of the proposed technology as level 4 and the target TRL after the proposed work as a level 5 was submitted on September 17, 2021.

Commercially available polymeric-amine sorbents on ultra-low pressure drop monolithic contactors are used in a novel high-fidelity, energy optimized modular design with integrated field units to capture CO₂ from air and mixtures of air and flue gases, producing high-quality CO₂ (gas and liquid), and utilizing recoverable waste heat from industrial processes to decrease the cost of market-ready DAC CO₂.

To attain TRL 5+, a multiple monolith DAC system with integrated heat recovery skid and CO₂ upgrading skid was built and tested at the NCCC for a cost of \$3.15M. Phase I was an engineering design phase for the integrated systems. Phase II was construction of the integrated systems with factory acceptance testing. Phase III included multi-campaign operations of the integrated system at the NCCC facility. A group (or “grove”) of eight individual DAC systems has been manufactured

and is being sent for a commercial project execution in the United Arab Emirates (Project Hajar). The project delivers a high-fidelity commercial prototypical system and will be tested under relevant real-world operation conditions. The system integration and design match the expected commercial design in most respects. The DE-FE0031961 project significantly advanced the maturity of the technology and provided a cost basis demonstrating commercially relevant operations in a real-world environment.

Under DE-FE0031961, Phase I was an engineering design phase for the integrated systems. Phase II involved the construction of the integrated systems with factory acceptance testing. Phase III, which concluded in July 2024, included multi-campaign operations of the integrated system at the NCCC facility. The project phases tested all the performance attributes listed below as required to advance the technology to a minimum TRL 5 which was the intended goal of DE-FE0031961. However, AC manufactured the DAC-100 embodiment deployed at the NCCC under DE-FE0031961 to be the same scale as the future commercial embodiment. These efforts referenced above and given the current duration of operations, along with the advancement to manufacture multiple units for commercial deployment, the TRL is 7+.

This project spanned the period of 10/01/20 to 7/31/24. Total cost-to-complete was \$3,151,805 (federal share plus cost share).

A final TMP which demonstrated an achieved TRL of 5+ was submitted on July 31, 2024. While the project required only being a TRL of 5+ as of completion, the technology was a 7+ on completion exceeding the original goal.

Work completed under DE-FE0031961 demonstrated the integrated system proven to work in “final form and under expected conditions.” Testing was performed in a real-world environment at NCCC. Additionally, AC is in the process of deploying a commercial embodiment (Project Hajar) to achieve TRL 8 with planned system commissioning and commercial operations occurring through the remainder of 2024. Project Hajar, as of late October 2024, is progressing through the commissioning plan at the commercial site. This commercial embodiment will consist of 8 DAC units arranged in a grove to supply CO₂ for geologic sequestration.

The advancement beyond TRL 7 will be based on the integration of the heat/steam supply into the DAC system from a commercially relevant site, together with requisite compression and full system heat integration and recovery. The DE-FE0031961 project also focused on developing a prototypical system designed for manufacturability. With the development work following the successful completion of DE-FE0031961, AC’s DAC technology will advance to TRL 8 with the execution of Project Hajar. The advancement to TRL 8+ was beyond the scope of the DE-FE0031961 project. Project Hajar was independently developed and financed, but lessons learned from DE-FE0031961 were applied to its engineering design.

With TRL 7 being attained, it is anticipated that multiple prototypical systems will be deployed in commercial operations to gain the operational readiness level required for large-scale manufacturing and deployment of the technology. Currently, commercial systems based on the same design are being manufactured and are anticipated to be put into operation with customers in 2024 and beyond.

Subtask 1.3 – Cross-cutting Project Management and NCCC Site Access

In accordance with the SOPO, detailed briefings were prepared for presentation to the NETL Project Manager at a project kick-off meeting held within ninety (90) days of the project start date. Annual briefings were also delivered to explain the plans, progress, and results of the technical effort, as well as a final project briefing at the project's close.

NETL's Project Kickoff Meeting

In February, SSEB and AC staff coordinated their participation in NETL's virtual Direct Air Capture Kickoff Meeting on February 24-25, 2021, and virtual Project Kickoff Meeting on April 16, 2021. Kimberly Gray, SSEB, and Matt Atwood, AC, delivered presentations on the objectives and work plan for the project, entitled "Direct Air Capture of Energy for Carbon Capture, Utilization, and Storage (CCUS) Partnership (DAC RECO₂UP)." Milestone 1.3.a, *Participate in NETL Kickoff Meeting*, was achieved on April 16, 2021.

Annual Project Reviews/Briefings

During August 2021, SSEB, AC, and CRI staff participated in NETL's virtual Project Review Meeting, with Capture Technologies being presented August 12-19, 2021. Kimberly Gray, SSEB, and Matt Atwood, AC, delivered the DAC RECO₂UP presentation on August 19, 2021.

On August 16, 2022, Matt Atwood, AC, delivered the DAC RECO₂UP presentation during the 2022 FECM/NETL Carbon Management Research Project Review Meeting. Patricia Berry and Ben Wernette, SSEB, participated in the 2022 FECM/NETL Carbon Management Research Project Review Meeting in Pittsburgh, PA, August 15-19, 2022.

Patricia Berry, Ben Wernette, and Nicholas Kaylor, SSEB, participated in the 2023 FECM/NETL Carbon Management Research Project Review Meeting in Pittsburgh, PA, August 28 – September 1, 2023. Joshua Miles, AC, presented, DAC RECO₂UP Technical Project Update, during the FECM/NETL Carbon Management Research Project Review Meeting on August 29, 2023.

On August 6, 2024, Joshua Miles of AC, delivered the DAC RECO₂UP presentation during the 2024 FECM/NETL Carbon Management Research Project Review Meeting. Patricia Berry, Ben Wernette, and Nicholas Kaylor, SSEB, participated in the 2024 FECM/NETL Carbon Management Research Project Review Meeting in Pittsburgh, PA, August 5–9, 2024.

Final Project Briefing

On July 29, 2024, NETL hosted the final project meeting for the DAC RECO₂UP project. Matt Atwood of AC presented a comprehensive accounting of the three-phased project to stakeholders and partners including AC, SSEB, NETL, and DOE staff. The presentation covered in detail the background, lessons learned, major milestones, testing, results and conclusions of the entire project. The presentation lasted over two hours with questions and answers composing the last half hour. The slides are available on the NETL Project Landing Page at <https://www.netl.doe.gov/project-information?p=FE0031961>.

Other Meetings as Requested

On October 4, 2021, SSEB's Patricia Berry and AC's Matt Atwood presented the DAC RECO₂UP project to NETL as a BP1 Review Meeting to support the Continuation Application for advancement into BP2.

On September 28, 2022, SSEB's Patricia Berry and AC's Matt Atwood presented the DAC RECO₂UP project to NETL as a BP2 Review Meeting to support the Continuation Application for advancement into BP3.

Patricia Berry and the AC team prepared documentation and a presentation for the NETL Peer Review. Patricia Berry and Matt Atwood, AC, participated in the virtual FY23 Carbon Dioxide Removal Peer Review meeting on June 9, 2023. In addition to the presentation, the DAC RECO₂UP team prepared and submitted a Project Technical Summary file to support the peer review process.

Due to a request from NETL, on November 7-8, 2024, Matt Atwood, Michael Vyvoda and Andy Mosely of AC, hosted a Technology Deep Dive, site walk through and Technology Overview at the NCCC around the AC DAC technology (Figure 3) to industry peers, and staff from the DOE, NETL and the NCCC.

On May 12-13, 2024, Michael Vyvoda and Andy Mosely of AC hosted a site walk through and technology overview at the NCCC around the AC DAC technology for industry peers and staff from DOE, NETL and the NCCC.

NCCC Site Access

To fulfill the scope of the project and conduct the DAC test campaign at the NCCC, it was required that the Project Team enter into a Technology Collaboration Agreement (TCA) with the NCCC. The TCA governed the terms and prerequisite analyses that were necessary prior to accessing the site.

Based on conversations between SSEB and the NCCC's John Carroll, it was determined that the TCA would need to be negotiated and executed as a bilateral agreement between NCCC and AC. SSEB requested an in-person meeting at the NCCC to further discuss the agreement and to allow AC's Matt Atwood and Bran Raskovic to tour the facility and the test bay area. On May 3, 2022, CRI's Dr. Gerald Hill met with Southern Company's John Carroll at the NCCC site to hold preliminary discussions regarding on-boarding of the test skids at NCCC. On May 4, 2022, SSEB's Patti Berry and Kimberly Gray and AC's Matt Atwood and Bran Raskovic toured the NCCC and met with operations staff.

Milestone 1.3.b, *Fully Executed NCCC Technology Collaboration Agreement and Other Access Agreements/Documents*, was achieved and verification documentation was shared with NETL on October 31, 2022.

Following execution of the TCA, AC worked with NCCC on HAZOP, technical screening, personnel training and clearance protocols, and planning in preparation for the DAC heat skid and other supporting equipment to be shipped on February 3, 2023, from California to Alabama. Planning work with NCCC progressed well with no delays.

The AC team arrived at the NCCC on February 7, 2023, underwent the onboarding process, and was granted unescorted access on February 8, 2023. The team began system setup and integration. Site visits were conducted to oversee and witness critical milestone achievements of the technology's development, including design, pre-site simulation testing, and commissioning/decommissioning. See "Subrecipient Monitoring" in Subtask 1.1 for additional information regarding management and oversight meetings and field trips.

At the conclusion of testing and post removal of the AC skids at the NCCC in July 2024, site access cards were relinquished to NCCC staff.

Throughout the time at the NCCC, AC received technical, operation and engineering support from the on-site operators, engineers and other NCCC personnel. Critical to the success of the first DAC project at the NCCC was open communication and collaboration from the NCCC. AC highly recommends any company to work with the NCCC to bring their next generation technologies to life.

Additional Briefings, Technical Presentations, and Featured Articles

While the DAC RECO₂UP scope of work did not support a formal outreach and engagement effort, the Project Team leveraged other opportunities to publicly share project activities and results on its website at sseb.org and through meetings and briefings, technical presentations, featured articles, and social media postings. Similarly, SSEB leveraged other outreach and educational opportunities at the NCCC to share the DAC RECO₂UP project details with the public as noted above in Subtask 1.1, the *Subrecipient Monitoring* section, of this report, which supplements the activities itemized below.

SSEB's 61st Annual meeting was hosted by Governor Kevin Stitt of Oklahoma on September 27-29, 2021. The meeting convened at the Omni Hotel in Oklahoma City, Oklahoma. During the Executive Committee meeting on September 27, Kimberly Gray, SSEB, presented the Board's Carbon Management Program, which included the DAC RECO₂UP project.

On December 5, 2021, SSEB's Ken Nemeth presented "*CCUS Commercialization: Leadership in the South*" virtually for the 2021 Midland CO₂ Conference. Material covered by the presentation included the high-level plans for the DAC RECO₂UP project.

During the SSEB Joint Annual Energy Briefing to Southern Legislative Leaders and Committee on Carbon Management meeting on July 9, 2022, in Oklahoma City, Oklahoma, SSEB's Ken Nemeth presented "SSEB Transcending Boundaries – Leadership in the South" that included the status of the DAC RECO₂UP project. State legislative leaders from across the Board's 18 member jurisdictions and its Associate Members (industry partners) attended the event.

On August 12, 2022, SSEB and the University of Houston hosted a meeting entitled, *Carbon Dioxide, Utilization, and Storage Technology Deployment and Hydrogen Market Development in Texas*. The agenda included presentations by leading CCUS experts to discuss technology commercialization opportunities, particularly in light of the hydrogen market development efforts in Texas. During the meeting, SSEB's Ken Nemeth presented the SSEB Carbon Management Program, including the latest news on the DAC RECO₂UP project.

On August 28-30, 2022, Governor Henry McMaster of South Carolina hosted SSEB's 62nd Annual meeting at the Marriott Hotel in Charleston, South Carolina. During the Executive Committee meeting on August 28, SSEB's Dr. Ben Wernette presented the Board's Carbon Management Program, which included the DAC RECO₂UP project and the status of the Design Phase.

On December 6, 2022, SSEB's Ken Nemeth participated in the 27th Annual CO₂ Carbon Management Workshop in Midland, Texas. He delivered a presentation on the impact of the Bipartisan Infrastructure Law on state and industry interest in carbon reduction technologies across the SSEB region. He also provided a summary of the DAC RECO₂UP project.

On May 16, 2023, SSEB's Ken Nemeth presented "Designing Energy and Environmental Programs to Meet Future Clean Energy Goals" during a meeting of the Florida Electric Power Coordinating Group. The presentation included a segment on the DAC RECO₂UP project.

During the SSEB Joint Annual Energy Briefing to Southern Legislative Leaders and Committee on Carbon Management meeting on July 8, 2023, in Charleston, South Carolina, Dr. Ben Wernette, SSEB, presented “New Energy Ventures Benefit Southern States – Leadership in the South” that included the status of the DAC RECO₂UP project and testing at NCCC. State legislative leaders from across the Board’s 18 member jurisdictions and its Associate Members (industry partners) attended the event.

SSEB’s 63rd Annual Meeting was hosted by South Carolina Governor Henry McMaster on September 27-29, 2023, in Greenville, South Carolina. The program included meetings of the Board’s Executive Committee and Associate Members, a business session, and multiple plenary sessions. During the SSEB Executive Committee meeting on September 27, Dr. Ben Wernette presented an update on the Board’s Carbon Management Program that included the DAC RECO₂UP project and ongoing test campaign at the NCCC. A highlight of the event was a keynote address provided by The Honorable Brad Crabtree, DOE’s Assistant Secretary for Fossil Energy and Carbon Management, on September 28. The FECM exhibit was also displayed throughout the conference, providing participants with a unique opportunity to explore FECM’s vast project portfolio including activities supported throughout the SSEB region.

The September 2023 edition of ***Carbon Capture Newsletter*** published by DOE/NETL featured a cover article entitled, “NCCC Announces First DAC Testing,” which briefly summarized the DAC RECO₂UP project (Figure 5). The newsletter was disseminated broadly to SSEB members at the Annual Meeting and copies were available at the DOE exhibit.

The 2023 CO₂ Conference was held in Midland, Texas, on December 4-7, 2023. On December 4-7, Dr. Wernette participated in the event in person, and Ms. Gray and Dr. Kaylor attended remotely. Dr. Wernette presented “Gigaton-Scale Projects and Supporting Work in the Southern States Energy Board Region,” which included a brief mention of the DAC RECO₂UP project.

CARBON CAPTURE NEWSLETTER

U.S. DEPARTMENT OF ENERGY | OFFICE OF FOSSIL ENERGY AND CARBON MANAGEMENT | NATIONAL ENERGY TECHNOLOGY LABORATORY



HIGHLIGHTS

The newsletter is compiled by the National Energy Technology Laboratory to provide information on recent activities and publications related to carbon capture.

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NCCC Announces First DAC Testing

The U.S. Department of Energy's (DOE) National Carbon Capture Center (NCCC) completed its first direct air capture (DAC) onsite test, in collaboration with Southern States Energy Board (SSEB) and Aircapture. SSEB, Aircapture, and other team members in the DAC Recovery of Energy for Carbon Capture, Utilization, and Storage (CCUS) Partnership are working together to scale up and demonstrate a modular and scalable atmospheric carbon dioxide removal system. The technology employs solid-amine adsorption-desorption contactor technology in integrated field units that produce a carbon dioxide (CO₂) stream of at least 95% purity using low-grade waste heat. The NCCC is assisting with commercially relevant field testing after design, construction, and initial testing by Aircapture. The project's technology demonstration involves using specialized equipment that pulls in ambient air, removes CO₂ molecules, and subsequently isolates and concentrates them for storage or conversion into valuable products. Funded with support from DOE's Office of Fossil Energy and Carbon Management (FECM) and National Energy Technology Laboratory (NETL), the experiments at the NCCC involve evaluating the efficiency and effectiveness of the DAC system, exploring different capture materials, and optimizing CO₂ extraction and storage processes.

Figure 5 – Carbon Capture Newsletter featuring the DAC RECO₂UP project on the cover, September 2023.

Task 2.0 – Technology EH&S Assessment and Risk Management

Subtask 2.1 – NEPA Compliance

All locations used in the performance of the DAC RECO₂UP project received a National Environmental Policy Act (NEPA) Categorical Exclusion (CX) dated September 14, 2020.

In April of 2022, AC moved its principal manufacturing facility from Oakland to Berkeley, California. Additionally, the performance location of Dr. Amy Landis (vendor) changed since the project's NEPA CX was received. An updated Environmental Questionnaire was completed and submitted to NETL. NEPA CX was approved for the new locations on April 19, 2022.

Subtask 2.2 – Technology EH&S Assessment

An assessment of Environmental Health and Safety risks was required as one of the final deliverables. The EH&S document addresses all the potential ancillary or incidental air and water emissions and solid wastes produced from the technology and the estimated magnitude. The compliance and regulatory implications of the technology were also addressed with reference to applicable U.S. EH&S laws and associated standards including the Comprehensive Environmental Response and Liability Act of 1980 (CERCLA), Toxic Substances Control Act (TSCA), Clean Water Act (CWA), Clean Air Act (CAA), Superfund Amendments and Reauthorization Act (SARA) Title III, and the Occupational Safety and Health Act (OSHA). Precautions for safe handling and conditions for safe storage were developed and detailed in the document.

The technology EH&S assessment began in March 2021. SSEB, AC, and CRI met on April 23, April 30, and May 7, 2021, to discuss the EH&S guidance provided in the SOPO. In addition, CRI's Dr. Gerald Hill worked with the NCCC's John Carroll to identify their expectations for DAC field testing and EH&S and HAZOP policies/procedures that may be applicable to the project.

The EH&S findings are as follows:

- No contaminants from the feed gas stream are anticipated, as it is air;
- No environmental degradation products are anticipated;
- Discharge is anticipated to be CO₂ lean air, and water condensate;
- No toxicological effects from materials in the process are anticipated;
- No volatile, flammable or explosive compounds are anticipated to be used in the project;
- No potentially hazardous materials are anticipated to be used on this project; and
- CO₂ gas monitors will be installed to ensure no buildup of unsafe amounts of CO₂.

Milestone 2.2.a, *Preliminary EH&S Assessment*, was drafted, reviewed, and submitted to NETL on June 16, 2021. On June 29, 2021, NETL requested that certain changes/clarifications be made to the Preliminary EH&S Assessment. The modified Preliminary EH&S Assessment was submitted to NETL on October 13, 2021. This deliverable also served as the verification document for the completion of Milestone 2.2.a, *Complete Preliminary EH&S Assessment*.

Deliverable 2.2.b, *Technology EH&S Assessment Update, Post-Field Testing* was submitted to NETL on July 31, 2024. There were no significant changes.

Subtask 2.3 – Risk Management & HAZOP Analysis

On September 20, 2021, SSEB, AC, and CRI conducted a EH&S Risk Workshop. Results of the workshop were tabulated in a EH&S Risk Register. The Risk Register addresses five specific chemicals and materials of interest, (1) Polyethyleneimine (PEI) and PEI-carbamate, (2) methanol, (3) cordierite, (4) gamma alumina oxide, and (5) titania oxide. These are components of Global Thermostat's Sorbent Apparatus. In addition, the Risk Register addresses specific aspects of workers' health and safety. Risk Management & HAZOP Analysis work was performed on the heat integration system and DAC skid.

A preliminary Pre-Operational Risk Management and HAZOP report was prepared by AC and submitted to the NCCC on January 30, 2023. The NCCC responded with comments and questions on February 15th, and AC submitted responses on February 16, 2023.

AC drafted and SSEB reviewed Deliverable 2.3.a, *Pre-Operational Risk Management and HAZOP Report*. The report was submitted to NETL on May 8, 2023.

Task 3.0 – Design and Verification of Integrated DAC and Energy Recovery System

Subtask 3.1 – Design and Costing of Integrated System

AC collaborated with Synapse Product Development, to conduct engineering design, an example of which is shown in Figure 6, of a DAC skid and a heat recovery skid, along with integration of system components and interconnection with host site facilities. The team developed an efficient design capable of demonstrating energy recovery and DAC costs. Work included preliminary identification and coordination of key procurement items, lead times, and confirmations of construction schedule.

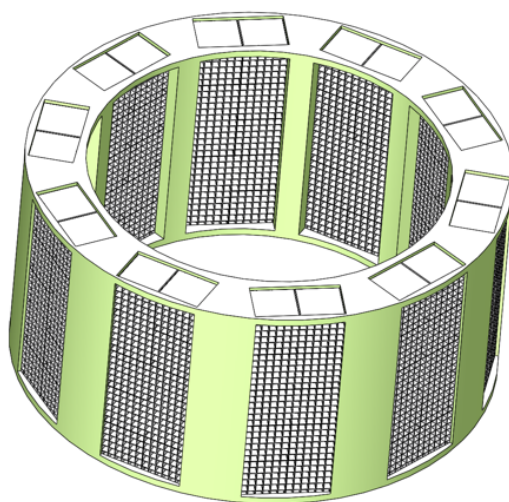


Figure 6 – Final design configuration

Process Flow Diagram (PFD), Piping & Instrumentation Diagrams (P&ID) and mass and energy balances for the Heat Skid and DAC skid were completed. A detailed bill of materials (BOM) was generated from the basic engineering documents and vendors were identified for all key process equipment. Lead time and availability for all key process equipment and associated was verified with vendors. Focus on equipment selection was based on: (1) components manufactured in the United States, with shorter or acceptable lead times; (2) component reliability and durability; and (3) economics and other manufacturing factors such as design for manufacturability for commercial DAC systems.

Key procurement items and design basis of the system components are as follows: Primary items for the DAC skid include the drum chamber, desorption chamber, fan, and duct. AC and Synapse completed the drum design (contactor & sorbent assembly) utilizing materials and fabrication methods that will reduce the overall system cost and increase overall system efficiency utilizing manufacturing and fabrication methods that are suited for large-scale commercial manufacturing and have low embodied carbon emissions. AC and Synapse completed detailed analysis with vendors to get tooling quotes and design for manufacturing cost estimates. AC and Synapse created a design for the desorption chamber assembly with input from Computational Fluid Dynamic (CFD)

and process simulation to ensure even steam flow characteristics and to confirm the system process timing model and CO₂ purity. The desorption chamber design was completed to reduce overall system costs, durability, maintenance requirements and to ensure commercial manufacturability. A high-performance fan was selected together with integrated engineering design utilizing CFD to maximize system efficiency, reduce pressure drop (energy demand) and to meet commercial maintenance requirements. Mechanical controls and movement designs were completed for the movement of the drum chamber (contactors) and desorption chamber. Remaining system process components and instrumentation was identified and integrated into the overall skid design.

The design of the heat integration skid was completed to utilize our host site NCCC's available steam and utilities to provide process heat for desorption. Primary items for the heat integration skid include process steam heat exchangers, steam accumulators, valving, instrumentation, and control systems. Basic design and integration of these components was completed toward an integrated heat process skid capable of accepting steam available from NCCC and generating steam of various qualities to the DAC skid.

The design basis and costing was verified through a preliminary TEA and process validation via chemical process simulation and integrated heat model. CFD modeling validated the energy consumption expected for the DAC system and was within commercially acceptable requirements and met the success criteria performance of the PMP – both for the pressure drop of the overall system (electricity) and desorption heat demand (thermal heat).

An overall chemical process simulation was completed integrating the heat exchange skid with the DAC skid validating the overall system energy demand, production capacity and CO₂ purity and met commercially acceptable design and performance success criteria as outlined in the PMP. All equipment lead times were identified and evaluated against a construction schedule and timing. Design direction and procurement favored shorter-lead time options on equipment to avoid any delays of the project schedule due to procurement and discussions with vendors verified availability of this equipment. All key process equipment lead times were below ten weeks from procurement to delivery. Milestone 3.1.a, *Complete Design and Cost Basis*, was completed on September 30, 2021. The project block flow diagram is shown in Figure 7 with the unit descriptions following.

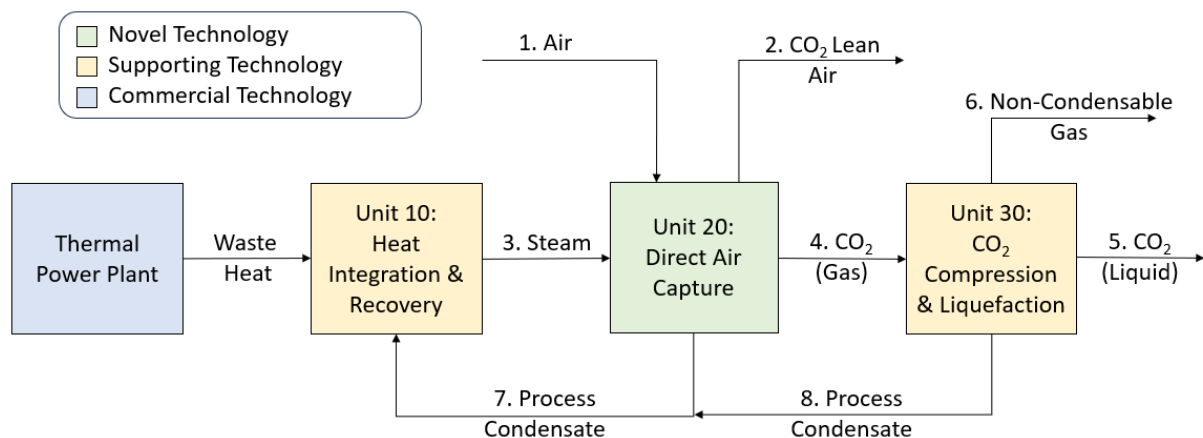


Figure 7 – Project Block Flow Diagram

Unit 10 – Heat Integration

This process unit takes the supplied waste heat steam from a stack and treats it to the desired process conditions for DAC regeneration. A pressure reducing valve reduces the intermediate steam to the desired pressure for use with individual process equipment. Additionally, this unit contains process condensate collection and water treatment to re-use the water as boiler feed water.

Unit 20 – Direct Air Capture Unit

This process unit captures CO₂ from atmospheric air and releases a concentrated CO₂ exhaust stream that will be conditioned for downstream use.

The DAC technology employs a polymeric amine sorbent, PEI, on a commercially available contactor substrate to capture CO₂ from ambient air. The two-step temperature vacuum swing adsorption process begins with moving ambient air across a low pressure drop monolithic contactor that adsorbs the CO₂ from the incident air stream (adsorption/capture mode), followed by desorption of the CO₂ and regeneration of the sorbent using steam, preferably generated from waste heat (desorption/regeneration).

Ambient air from the battery limit (B.L.) is drawn through a contactor-sorbent substrate using fans at an optimized frontal velocity.

The DAC system reduces energy required for capture by employing ultra-low pressure drop contactors operating in laminar flow that minimizes the required pressure drop and therefore energy. Carbon dioxide is selectively adsorbed from ambient air via perpendicular diffusion through the mesoporous walls of the contactor. The CO₂ then binds to the sorbent amine sites driving a reduction of the partial pressure of CO₂ gas in the contactor, creating a mass gradient that draws CO₂ further into the walls.

The small size of the monolith channels yields a high CO₂ mass transfer rate at the given air velocity and contactor depth. Regeneration of CO₂ uses low-grade saturated steam to release CO₂ from the sorbent which is then collected. A vacuum is applied prior to steam regeneration to remove air from the contactor void volume, improving CO₂ product purity and reducing oxidative damage to the sorbent at elevated desorption temperatures.

The DAC system is an integrated machine enabling an optimized adsorption period followed by desorption period wherein multiple contactor assemblies share a common fan and desorption chamber infrastructure. The monolith contactors collect CO₂ from ambient air flow.

Unit 30 – CO₂ Compression and Liquefaction

This process unit takes the process vapors from the DAC Unit and modifies the temperature and pressure suitable for liquefaction before liquefying the CO₂ into a liquid CO₂ product of over 99.9% purity. Three main steps occur inside this unit: compression, dehydration, followed by liquefaction. Liquid CO₂ product is stored in the unit as well. Non-Condensable gas consisting of nitrogen and oxygen is vented to the atmosphere (B.L.).

Major design and engineering efforts are listed below:

- Conceptual design for sorbent apparatus layout and transport completed. Included considerations of brick layout and orientation to optimize airflow (with respect to pressure drop, uniformity of airflow) and even steam flow across sorbent apparatus and system component configuration.
- Timing model for various process steps developed. Factors considered included, but were not limited to, sorbent apparatus configurations, adsorption process parameters and timing, desorption process parameters and timing, motion control timing, valve and motorized component movement times, system uptime, etc.
- Airflow and desorption chamber architecture design work was completed (design of sealing mechanism, pipe sizing, fan integration, etc.).
- Computational fluid model (CFD) developed; CFD modeling and analysis and alignment with system architecture was performed using Ansys 2020R2 throughout this analysis. Thermodynamic modeling of the contactor and sorbent substrate was performed to provide input variables to the CFD models. Geometries were created in SolidWorks 2018 and meshed in Ansys Mesher. All CFD runs used Fluent. More than 45 different simulations were performed over the period.
- Initial steam chamber design input into CFD, and simulation runs performed to ensure even steam flow characteristics and confirm timing model and CO₂ purity designs.
- Component selection (motors, fan, prefilters, drive mechanisms, etc.) with a focus on (1) components manufactured in U.S., with shorter lead times; (2) component reliability and durability; (3) economics, and other manufacturing factors.
- PFD, P&ID and mass and energy balances for the heat integration skid were completed and a design review occurred.
- The Waste Heat Availability and Integration Study.

Subtask 3.2 – Preliminary (Commercial/Process) Design Check

Based on the design work in Subtask 3.1, the team prepared a chemical process and energy utilization model. The model informed the preliminary TEA and LCA design and provided a basis for demonstrating a reduction in cost of DAC.

Deliverable 3.2.a, *Integrated System Process and Heat Model*, which was submitted to NETL on October 5, 2021.

Task 4.0 – Construction and Testing of Integrated Systems

Subtask 4.1 – Construction of Skids

Task 4.0 activities commenced on November 1, 2021, upon approval of BP2.

Following the design basis from Task 3, skid construction began on February 9, 2022. Testing of selected instrumentation and related equipment started on February 3rd, and framing construction began on February 9, 2022. To prepare for construction during BP 2, AC and Synapse completed detailed engineering drawings and a BOM containing component part information (e.g., part number, quantity, vendor, price, lead times, etc.) required to begin procurement. Procurement on long-lead time items and specialty/critical process equipment with long lead times was completed. Construction, including building the framing for the skids and testing electrical and component parts and instruments was completed.

The project team encountered changes in lead times for certain equipment between specifying the equipment, vendor selection, and lead time estimation during BP1, and final lead time quotes once the detail engineering was complete and parts ordered. This unprecedented supply chain interruption required additional work to ensure that the project construction timeline remained on schedule, including adjusting construction planning and procurement ordering. As a result, the team took action to mitigate construction schedule impacts including, but not limited to, the priority ordering of parts first directed to long-lead items such as the fan, motor index drive, and the dial plate and revised assembly order to accommodate for process equipment availability. Figure 8 depicts the completed Heat Skid at AC.



Figure 8 – Completed Heat Integration Skid



Figure 9 – Mid Construction DAC-100 and Heat Skid

Despite the delays caused by the supply chain disruption, completion of Milestone 4.1.b, *Finish Construction of Skids*, was achieved on schedule. SSEB submitted the Letter Report verifying that Milestone 4.1.b was reached on July 31, 2022. Figure 9 depicts the DAC-100 mid-construction at AC.

Subtask 4.2 – On-site Simulated Commissioning and Integration of Skids

Subtask 4.2 began August 1, 2022, with commencement of purchasing component parts to integrate the various skids to each other, to the DAC, and to the test rig.

The skids were tested separately through phases and integrated. Testing on the integrated system commenced in phases.

The DAC design basis included the utilization of high-efficiency commercially available vane-axial fans¹ to draw air through monolithic PEI-coated contactors positioned on a rotating indexing base-table through a stationary desorption chamber.

An integrated heat skid was designed and built to model a variety of heating levels available from industrial sources to meet the steam thermal demand for DAC desorption. The heat skid includes a wet-steam accumulator and a steam de-superheater to test various configurations of system

¹ Greenheck model AX-113-275-0914-B100

thermal demand towards the completion of an integrated TEA and LCA for DAC systems utilizing waste-heat from industrial sources.

AC's commissioning schedule (Table 3) was delayed due to several supply-chain challenges resulting in fewer test days available to optimize system performance and configuration than planned. Key utilities at the AC Berkley California based facility such as steam supply (boiler lead time), installation and component parts delayed commissioning. Additionally, delivery of the contactors from GT's supplier was delayed from schedule.

Table 3 - Commissioning Schedule

	Purpose	Completion Date
DAC Cold Commissioning 1 (no contactors)	System commissioning to test system configuration, control system and interlocks without contactors.	8/10/22
DAC Cold Commissioning 2 (uncoated contactors)	System commissioning to test DAC system with pressure drop from unpotted contactors.	10/4/22
DAC Cold Commissioning 3 (coated contactors)	System commissioning to test DAC system with pressure drop from potted contactors.	10/19/22
Heat Skid Commissioning 1 (without steam filters)	System commissioning to test heat skid system configuration, control system, safety systems and interlocks, steam purity.	9/23/22
Heat Skid Commissioning 2 (with steam filters)	System re-configured to add steam filters to remove traces of Fe from boiler.	10/18/22
Hot Commissioning (Integrated DAC & Heat skids)	Integrated system testing of heat skid providing steam to DAC skid, and CO ₂ collection.	10/24/22

Cold commissioning of the DAC skid without contactors was completed on 8/10/2022. Cold commissioning included evaluation of fan performance curves with various contactor types and full automation of system prior to hot commissioning with steam on PEI-coated contactors.

Following mechanical completion of the heat skid, it was pressure tested and the control system configuration was tested. Following pressure testing, initial hot commissioning with steam from an on-site boiler was completed and tested for full system automation and testing of safety systems on 9/23/2022. The heat skid was then insulated, and final hot commissioning was completed. Safety and HAZOP analysis were conducted during operations to ensure fail-safe operations of the control system.

Integrated system hot commissioning was completed on October 24, 2022. Integrated system hot commissioning included connection of the heat skid to the DAC skid.

Subtask 4.3 – Data Analysis & Operational Testing Planning

Simulated commissioning and operational data collected in Subtask 4.2 were checked against the model from Subtask 3.2 to ensure operational parameters were sufficient to warrant transportation to the National Carbon Capture Center and long-term testing in an integrated system environment.

An initial operation testing plan was created and shared with the project partners. The plan consisted of three separate 700 hour test campaigns. This plan was adapted during subtask 5.2 due to having increased availability at the NCCC testing bay.

Milestone 4.3.a, *Finish Phase II Commissioning Report and Test Matrix*, was completed on October 31, 2022.

Task 5.0 – Long-Term Testing in Integrated System Environment at NCCC

Subtask 5.1 - Transportation, Site Integration & Site Commissioning

On February 3, 2023, the DAC system, which includes the Heat Skid, DAC Unit, vacuum pump, liquid chiller, main control panel, tools and spare parts were shipped from AC's fabrication facility in Berkeley, CA and arrived at the NCCC facility in Wilsonville, AL on February 7, 2023. Milestone 5.1.a, *Skids Transported to the NCCC*, was completed and verified with an email regarding the arrival of the skids at the NCCC on February 7, 2023. The DAC-100 and heat skid being prepped for shipment is depicted in Figure 10.



Figure 10 – DAC-100 and Heat Skid preparing for shipment from AC's Berkley facility

Site integration proceeded during February 2023. AC installed cable piping interconnections, hooked up temporary 24VDC power to perform signal checks, performed pressure testing on all piping and performed selected other activities. Integration activities were suspended on February 10, 2024, due to challenges with electrical connections and certification of certain equipment that needed to be altered to comply with the OSHA/NEC requirements for operation for industrial installation.

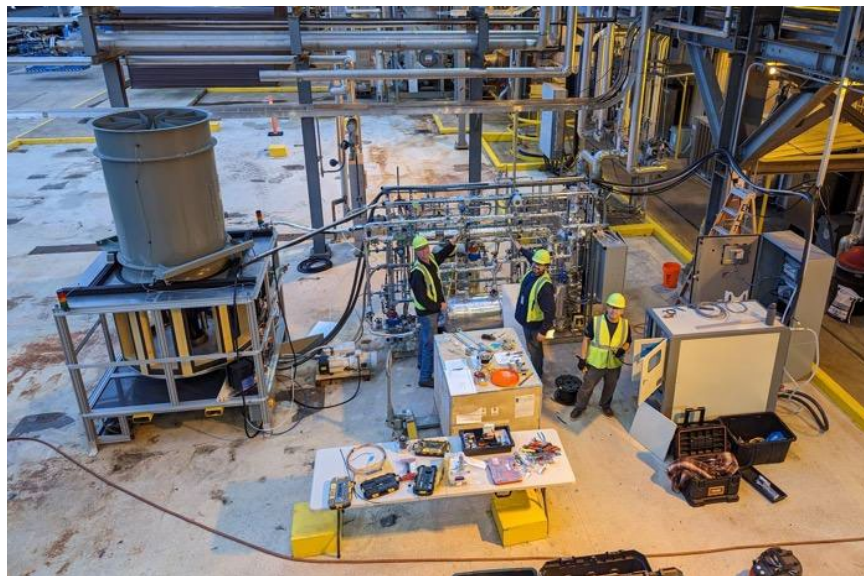


Figure 11 – DAC-100 and Heat Skid undergoing installation at the NCCC

During March 2023, site integration resumed. AC removed all the power cables and installed new power cables, modified control panels to install new flex conduit, installed new conduit, etc. AC also repaired a damaged part due to a storm and installed various weather-related awnings. Figure 11 depicts the DAC-100 and Heat skid undergoing installation at the NCCC.

In April 2023, AC's operations and commissioning team finalized installation of the DAC at the NCCC site. Commissioning of the unit was conducted along with the first capturing of CO₂ at the site on April 28, 2023.



Figure 12 – DAC-100 and Heat Skid installed and operational at the NCCC

Deliverable 5.1.a, *Site Commissioning Report & Final Operational Plan*, and Milestone 5.1.b, *Complete Site Commissioning at NCCC and Final Operational Plan*, were submitted to NETL on May 15, 2023. Figure 12 depicts the DAC-100 and Heat Skid installed and operational at the NCCC.

Subtask 5.2 – Site Operations & Testing

Four main test campaigns were performed at the NCCC while a final fifth campaign ran at the end of testing at the NCCC to take advantage of a further extension on site. The first campaign was designed to verify optimum running conditions of the DAC + Heat Integration skids and ensure steady state operations in a changing environment. The second test campaign was devised to verify availability of the DAC with as little operator intervention as possible. Campaign 3 had two objectives. Campaign 3a aimed to find optimal running conditions for integration with the liquefaction skid using a new chiller on site. Campaign 3b was designed to create a liquid stream, 99.9% CO₂, by mole, at NCCC. These were the original campaigns that were first set out in the scope of work. Each total campaign was to take place for at least 700 hours of operation. In addition to the original three campaigns, additional fourth and fifth campaigns were designed once AC received authorization to continue testing through mid-July of 2024. This fourth campaign had several goals, described below, with the primary goal to continue steady-state testing of the DAC system to inform future design work. The fifth campaign took place after a planned shutdown of utilities by NCCC staff at the facility. The fifth campaign's main goal was to increase the amount of cycles on the machine during the high heat and high relative humidity of the summer at the site.

Five testing campaigns were conducted at the NCCC since the DAC arrived on site in April of 2023. The DAC unit operated for 3,395 hours, running 167,025 adsorption cycles. This equates to over 141 days of DAC operation. Summary of the key findings are shown in Table 4. Figure 13 depicts the DAC-100, Heat Skid and Liquefaction skid operating during test campaign 4 at the NCCC.

Table 4 – Key Findings from Test Campaigns

Test Campaign	1	2	3A & 3B	4	5
Hours Completed	700+ hrs.	700+ hrs.	1110+ hrs.	690+ hrs.	180+ hrs.
Goal Achieved or Key Learning	Optimization and initial Run-data	>90% Availability	>99.9 Mol% Liquid CO ₂	Qualifying Alternative Suppliers, Cont'd Run Data	Fatigue Testing, Ran alternative cycle times



Figure 13 – DAC-100, Heat Skid, and Liquefaction container installed and operational at the NCCC

System behavior, variations in CO₂ production, faults, and failures observed during this period were used to refine and improve the procedures according to which the DAC is manufactured and operated. Testing was complete on July 7, 2024. A letter report which verified completion of Milestone 5.2.a, *Complete DAC Testing at NCCC*, was submitted to NETL on July 31, 2024.

Subtask 5.3 - Decommissioning

AC and the NCCC decommissioned the skids from July 8 to July 12, 2024. On July 25, 2024, the liquefaction skid was shipped from the NCCC to AC's Berkeley California office. On July 29, 2024, the DAC-100 Skid, heat skid and all remaining items were shipped to AC's Berkeley, California, office. A letter report verifying completion of Milestone 5.3.a, *Complete Decommissioning and Removal of Skids from Host Site*, was submitted to NETL on July 31, 2024. Figure 14 depicts the decommissioning efforts at the NCCC.



Figure 14 – DAC-100, Heat Skid, and Liquefaction container being decommissioned at the NCCC

Task 6.0 – Data, Techno-Economic, and Life Cycle Analyses

Subtask 6.1 – Data Analysis, TEA, and LCA

Data Analysis was conducted throughout the testing campaigns. The primary benefit of the Test Campaigns was to provide a sizable and varied database of in-field operational data for analysis and modeling. A focus for future DAC improvements is multivariate analysis and Design of Experiments testing, in which multiple system inputs (e.g., ambient temperature, RH, fan speed, contactor array material, steam injection time) are evaluated and quantified with respect to their effects on a given response (e.g., CO₂ production, power consumption, cost). The NCCC Test Campaigns have in sum generated a database of over 150,000 data points, collected over a wide range of atmospheric conditions and machine setpoints, that can be used to inform predictive DAC performance models, evaluate contactor behavior and performance, and allow for in-depth comparison between differing design paths.

A Pre-Screening TEA, a Pre-Screening LCA, and an Updated State Point Data Table were completed as part of the final deliverables. Milestone 6.1.a, *Complete Pre-screening Techno-Economic Analysis and Life Cycle Analysis*, was submitted to NETL on July 31, 2024, in the form of a letter report.

Deliverable 6.1.b, *Pre-screening Techno-Economic Analysis*, was completed on July 31, 2024

Updated designs for AC have achieved a greater than 50% decrease in the cost of manufacture for the DAC-100 unit. A picture of the updated design operating outside the Aircapture offices in Berkeley can be found in Figure 15.



Figure 15 – DAC-100 revised design operating at AC in April of 2024

A model was created in Aspen Plus to predict the experimental data for an average production of CO₂ on a per hour basis using the data generated from the test campaigns listed above.

Deliverable 6.1.c, *Pre-screening LCA*, was completed on July 31, 2024. The LCA evaluated two versions of the DAC unit: a first-generation design, SN1, and the latest design as of July 2024, SN3. SN1 was a commercial prototype tested at NCCC from April 2023 to July 2024. SN3, manufactured in February 2024, utilized many of the lessons learned from the test campaigns at NCCC along with learnings from running a similar design to SN1 at AC's office in Berkeley California SN2 from February 2023 to January 2024. SN3 uses more robust materials that were selected for ease of sourcing, lowering the cost of manufacture, and decreasing the LCA impact. Additionally, improvements were made to the system design to decrease utilities and increase reliability.

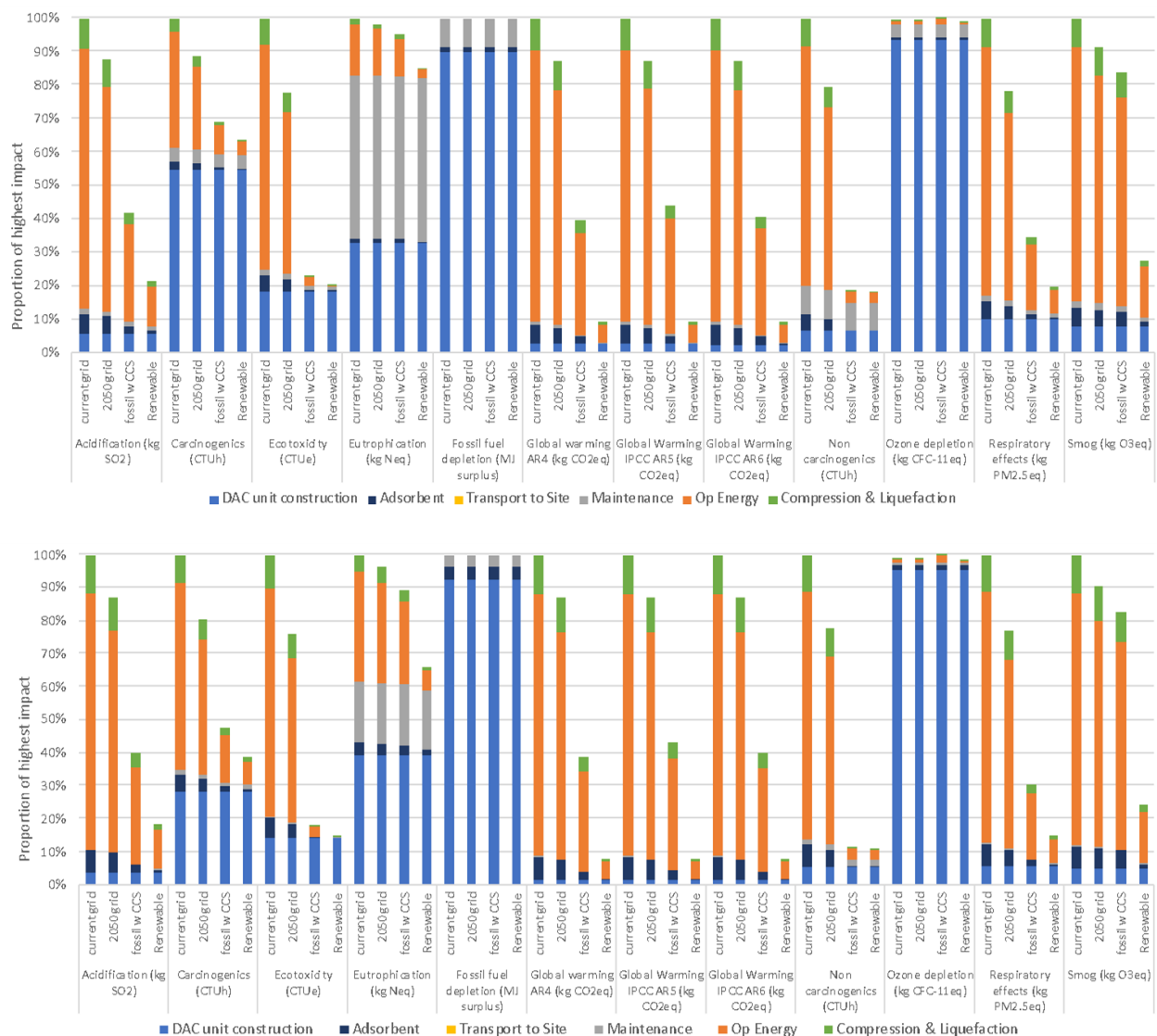


Figure 16 – Comparing DAC-100 SN1 and DAC-100 SN3

The results from the LCA, as shown in Figure 16 with the top figure showing SN1 and the bottom figure showing SN3, indicate significant improvements to the environmental impacts of the DAC unit design, reducing impacts of the unit construction by nearly fifty percent in most environmental impact categories. These environmental impact savings are realized most in the carcinogenicities, eutrophication, fossil fuel depletion, and ozone depletion impact categories, reducing life cycle impacts by 50%, 63%, 77%, and 36% respectively from SN1 to SN3 for the current grid mix.

Most LCAs of DAC show that operational energy consumption is the driving factor contributing to life cycle environmental impacts (Wang et al. 2023). RECO₂UP carbon capture efficiency for all grid mixes assessed in this LCA are shown in Table 5. For the current grid mix using Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) methods, 1.37 kg CO₂ are emitted per kg of captured, compressed pipeline ready CO₂. Results in this LCA are similar to the literature that

find operational energy for CO₂ capture contributes to the majority of DAC impacts (Wang et al. 2023); in this LCA 79% of the global warming potential for SN3 using the current grid mix comes from operational energy. Improving the carbon emissions of the grid mix significantly improves the life cycle greenhouse gas emissions of DAC; the 2050 grid mix reduces greenhouse gas emissions from the current grid by 69%, while fossil energy with CCUS and renewable energy grid mixes reduce emissions by 30% and 5%, respectively. With a renewable energy grid mix, the CO₂ capture rate is improved from 1.37 (current grid) to 0.11 kg CO₂ emitted per kg of captured, compressed pipeline ready CO₂.

Table 5 – DAC RECO₂UP CO₂ capture efficiency using IPCC AR5 methods with grid mixes defined by DOE FOA for the SN3 system

Grid mix	Capture efficiency (kg CO ₂ are emitted per kg of captured, compressed pipeline ready CO ₂)
Current grid	1.37
2050 grid	1.19
Fossil power with CCS grid	0.59
Renewable grid	0.11

Conclusion

The DAC RECO₂UP project was successful at completing its goal of decreasing the cost of capture through the testing of a commercial scale DAC unit capturing concentrated CO₂ at over 95% purity. The DAC RECO₂UP project was the first DAC system installed and demonstrated at the NCCC in Wilsonville, Alabama. The NCCC provided a commercially relevant environment in which to assess the DAC solid-amine CO₂ adsorption-desorption contactor technology. Five testing campaigns were completed with an experimental period of over 3,300 hours, allowing the project team to obtain a sizable and varied database. The DAC RECO₂UP project achieved significant improvements to the environmental impacts of the DAC unit design and achieved the projects stated goal of advancing the TRL of the DAC technology. Throughout the time at the NCCC, AC received technical, operation and engineering support from the on-site operators, engineers and other NCCC personnel. Critical to the success of the first DAC project at the NCCC was open communication and collaboration from the NCCC.

The lessons learned from DAC RECO₂UP were implemented in the next generation of DAC machines which realized a decreased utility demand of twenty percent and a capital cost reduction of a DAC unit by over fifty percent. Optimizations are derived from an overall simplification of the design and by selecting easier to acquire materials of construction. Further optimization of the DAC system can be expected through co-locating multiple DAC modules together. This optimization work for a multi-DAC system was not part of DE-FE0031961 but was carried out as part of DE-FE0032160, Nuclear Direct Air Capture with Carbon Storage, and DE-FE0032157, Low Carbon Intensity Formic Acid Chemical Synthesis from Direct Air Captured CO₂ Utilizing Chemical Plant Waste Heat. During those two Front End Engineering Design (FEED) projects an eight DAC design layout that AC refers to as a “Grove” was created based on CFD analysis as well as combining utilities to lower electrical and cooling demand for the combined system. Key learnings from this project have paved the way for commercial roll outs of DAC machines to capture and store CO₂ for long term sequestration.

Project Hajar, a commercial project in the UAE utilizing AC’s DAC technology to mineralize CO₂, utilizes the lessons learned from DAC RECO₂UP as well as the two FEED projects mentioned above and is based on the DAC Grove design layout utilizing the improved DAC designs made possible through DAC RECO₂UP. Figures 17 and 18 depict the DAC units at project Hajar in the UAE. SSEB and AC will continue to collaborate while advancing DAC technology to capture for long-term storage CO₂ through the SEDAC Hub project (DE-FE0032392).



Figure 17 – Project Hajar during commissioning in October 2024



Figure 18 – Project Hajar during Hot Start in November 2024

List of Acronyms and Abbreviations

AC	Aircapture
ACH	Automated Clearing House
ASAP	Automated Standard Application for Payments
BL	Battery Limit
BOM	Bill of Materials
BP	Budget Period
BP1	Budget Period 1
BP2	Budget Period 2
BP3	Budget Period 3
CA	Continuation Application
CCUS	Carbon capture, utilization, and storage
CERCLA	Comprehensive Environmental Response and Liability Act of 1980
CFD	Computational Fluid Dynamic
CO ₂	Carbon dioxide
CRI	Crescent Resource Innovation
CWA	Clean Water Act
CX	Categorical Exclusion
DAC	direct air capture
DAC RECO ₂ UP	Direct Air Capture Recovery of Energy for CCUS Partnership
DMP	Data Management Plan
DOE	U.S. Department of Energy
DOE-FECM	U.S. Department of Energy Office of Fossil Energy and Carbon Management
EH&S	Environmental Health and Safety
FARC	Federal Assistance Reporting Checklist
FEED	Front End Engineering Design
FFACTA	Federal Funding Accountability and Transparency Act
FSRS	Federal Subaward Reporting System
GT	Global Thermostat
HAZOP	Hazard and Operability
IP	Intellectual Property
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
LCA	Life Cycle Analysis
NCCC	National Carbon Capture Center
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
OSHA	Occupational Safety and Health Act
P&ID	Piping & Instrumentation Diagrams
PEI	Polyethyleneimine
PFD	Process Flow Diagram
PMP	Project Management Plan
Project OASIS	Optimizing Alabama's CO ₂ Storage in Shelby County
R&D	Research and development
RPPR	Research Performance Progress Reports

SAM	System for Award Management
SARA	Superfund Amendments and Reauthorization Act
SCS	Southern Company Services
SF425	Federal Financial Report (form)
SN-1	Serial Number 1
SN-3	Serial Number 3
SOPO	Statement of Project Objectives
SOW	Scope of Work
SSEB	Southern States Energy Board
Synapse	Synapse Development Group
TCA	Technology Collaboration Agreement
TEA	Techno-economic Analysis
TMP	Technology Maturation Plan
TRL	technology readiness level
TSCA	Toxic Substances Control Act
UCC	Uniform Commercial Code