REACTIVE CARBON CAPTURE PROJECT REVIEW MEETING

NATIONAL RENEWABLE ENERGY LABORATORY
GOLDEN, CO

January 17–18, 2024

DOE/NETL-2025/5312

Disclaimer

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LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

4C	Center for Closing the Carbon Cycle
AI	Artificial intelligence
AMO	Advanced Manufacturing Office
ARPA-E	Advanced Research Projects Agency-Energy
BES	Basic Energy Sciences
BETO	Bioenergy Technologies Office
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CDR	Carbon dioxide removal
CO	Carbon monoxide
CO_2	Carbon dioxide
CRADA	Cooperative research and development agreement
DAC	Direct air capture
DOE	U.S. Department of Energy
FECM	Office of Fossil Energy and Carbon Management
FOA	Funding opportunity announcement
GHG	Greenhouse gas
H_2	Hydrogen
HDPE	High-density polyethylene
IEDO	Industrial Efficiency and Decarbonization Office
LCA	Life cycle analysis
ML	Machine learning
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
NO_X	Nitrogen oxide
NREL	National Renewable Energy Laboratory
OPEX	Operating expenses
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and development
RCC	Reactive carbon capture
RD&D	Research, development and demonstration
RNG	Renewable natural gas
SBIR	Small Business Innovation Research
TEA	Techno-economic analysis
TRL	Technology readiness level

EXECUTIVE SUMMARY

RCC CONCEPT AND CONTEXT WITHIN THE CARBON MANAGEMENT LANDSCAPE

The capture and conversion of carbon dioxide (CO_2) to carbon-based products (chemicals, fuels and materials) powered by carbon-free energy is one of the key pathways that can enable the circular carbon economy needed to achieve global CO_2 emissions reduction goals. Most CO_2 capture and conversion processes to date have been developed separately, but there have recently been efforts to combine these in an approach called reactive carbon capture (RCC). This is a process intensification scheme with the goal of reducing capital cost and energy requirements associated with CO_2 capture and conversion, which are becoming increasingly important with the rising demand and competition for limited renewable energy resources.

RCC involves the integration of CO_2 capture and conversion technologies without a separate process step to generate a purified CO_2 intermediate, and can be integrated with CO_2 capture from air or a point source. It spans several technology approaches, including thermochemical, electrochemical, biological and mineralization, and can result in products including chemicals, fuels and building materials. Additional information on the RCC concept and approaches is included in the **Background** section of this report.

MEETING STRUCTURE AND GOALS

The U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) and National Renewable Energy Laboratory (NREL) hosted the RCC Project Review Meeting January 17-18, 2024, at NREL in Golden, Colorado. The meeting was a follow-up of a prior meeting held in 2020, titled "Reactive CO_2 Capture: Process Integration for the New Carbon Economy." The goals of the meeting were to review currently funded RCC projects across multiple DOE offices to share lessons learned; to identify challenges, opportunities and research and development (R&D) needs in the field of RCC; and to identify opportunities for DOE to promote collaboration and support the advancement of RCC technologies.

The meeting attracted approximately 75 attendees with broad expertise from industry, academic institutions and national laboratories who are technology developers and subject matter experts. The agenda can be found in the **Appendix**. This report aims to summarize feedback and key themes from presentations and panel and breakout room discussions held throughout the course of the meeting.

PROGRESSION OF RCC SINCE 2020

The meeting highlighted that clear progress has been made on the development of RCC technologies since 2020, with numerous technologies currently at a proof-of-concept stage rather than a conceptualization stage. It is evident that recent DOE support has helped establish a pipeline of technologies that span catalytic, mineralization and biological approaches to RCC and a variety of CO_2 sources. Several of these technologies are now ready to move to the next Technology Readiness Level (TRL) and focus on demonstration in fully integrated systems. Besides R&D progress, there is now cross-office collaboration within DOE on RCC, as well as increased policy support and available markets for RCC technologies. A more detailed summary of the progression of RCC since the 2020 meeting is included in the **Reactive Carbon Capture Progression Since 2020** section of this report.

KEY THEMES

The following emerged as key themes and takeaways based on presentations and discussions by participants during the meeting.

RD&D Needs Based on Existing Challenges in the RCC Field

The overview of DOE-funded projects on RCC, as well as sessions highlighting industry and research activities, provided insights into the status of the RCC field and ongoing and emerging challenges. The following were identified as key areas of action needed to advance the field of RCC:

- Need to advance RCC technologies from proof-of-concept (TRL 2-3) to integrated systems (TRL 4 and beyond).
- Need for rigorous and consistent analysis, including techno-economic and life cycle analysis, to evaluate value proposition of RCC, product-market fit and process cost.
- Need to expand and diversify the portfolio of RCC technologies and product portfolios. Key directions for this effort could include reassessing existing processes with RCC in mind, reverse engineering RCC approaches to manufacture specific products from the petrochemical industry and investigating novel strategies for creating value/services from RCC concepts.
- Need for additional R&D on materials and processes for RCC. Efforts in this area could include co-optimization of materials and processes to maximize productivity, developing a fundamental understanding of reaction mechanisms and exploring new CO_2 reactivities afforded by RCC that can be leveraged to design improved approaches, and evaluating the impact of impurities on RCC processes to improve durability.

Opportunities for DOE to Advance the Field of RCC

Participants also discussed the potential for federal involvement, namely in the areas of technology development, pilot support, data gathering and establishing RCC hubs to help evaluate various technologies at all research, development and demonstration (RD&D) scales. Recommendations included:

- Aligning RCC efforts across DOE offices to provide multi-office funding, address TRL gaps, and create funding opportunities specifically for scale-up RD&D for RCC technologies.

- Creating RCC hub(s) and/or consortia to advance and evaluate various technologies at all RD&D scales and help facilitate scale-up partnerships and create teams to help reduce costs.
- Developing federally supported test facilities that can test technologies under real conditions and providing fast-track access to experts, researchers and national lab facilities for small start-up companies, all of which will support efforts required to de-risk commercialization of RCC technologies.

NEXT STEPS TO ADVANCE RCC

The review of the status of RCC during the meeting and the feedback from participants highlighted key areas for action that DOE can take to advance the field. These include cross-office engagement within various DOE offices to coordinate funding efforts and address TRL gaps; developing a roadmap that maps advancement of RCC technologies up the TRL ladder; providing additional funding opportunities in this space; and supporting future meetings focused on RCC to continue to promote collaborations between academia, national laboratories and industry. Additional items are included in the **Next Steps to Advance RCC** section of this report.

Note: The Federal Advisory Committee Act (FACA) does not apply to this meeting, as the purpose was to obtain information or viewpoints from individual attendees as opposed to advice, opinions or recommendations from the group acting in a collective mode.[1]

[1] When is Federal Advisory Committee Act (FACA) Applicable? http://www.gsa.gov/faca.

1 BACKGROUND

1.1 RCC CONCEPT AND CONTEXT WITHIN THE CARBON MANAGEMENT LANDSCAPE

The increased concentration of carbon dioxide (CO_2) in the atmosphere and its effects on global climate change call for an urgent and coordinated effort to research, develop and deploy technologies that mitigate CO_2 emissions. Electrification with carbon-free energy sources is necessary to achieve these goals. However, several segments of our economy (e.g., aviation, chemicals manufacturing) are hard to decarbonize and will continue to rely on carbon in the future. Thus, a circular carbon economy is needed, where CO_2 could be captured and utilized, serving as a feedstock for other carbon-containing products.

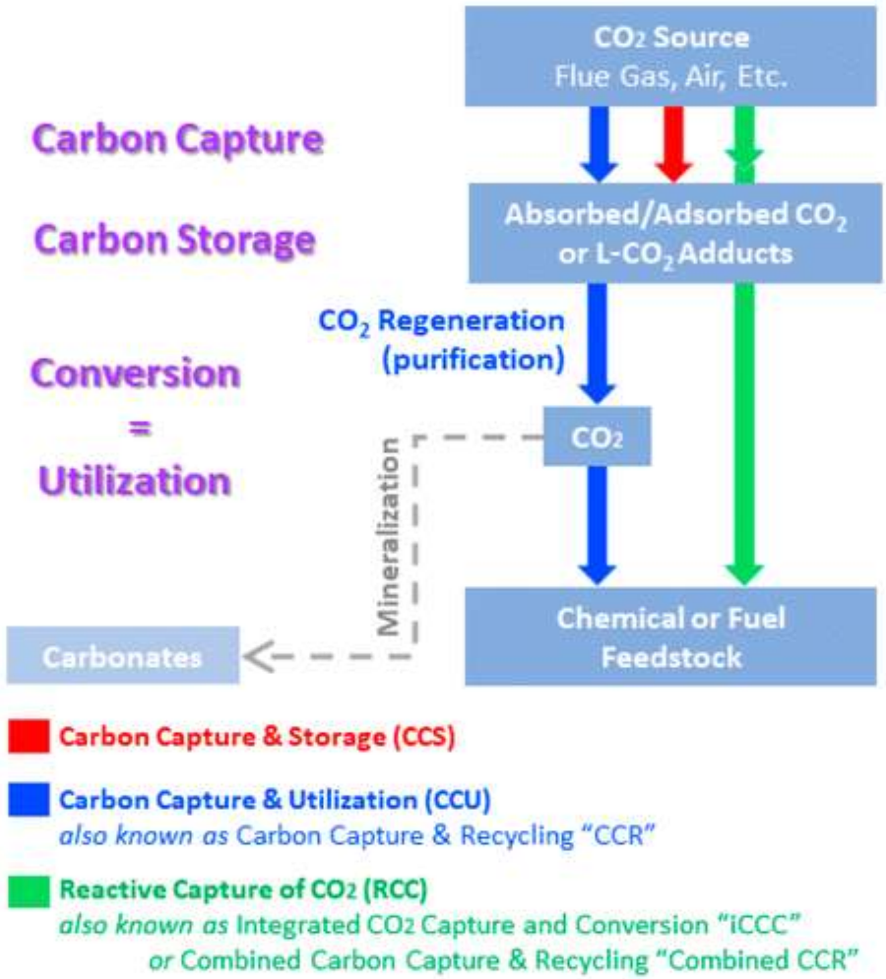
Carbon dioxide capture and conversion are energy-intensive processes, and, with the increasing demand for renewable energy to decarbonize multiple sectors of our economy, it is crucial to develop approaches to reduce the energy requirements associated with CO_2 transformation into carbon-based products. Most carbon capture and conversion processes that have been developed to date have been studied independently and involve conducting these steps separately. In these schemes, the output CO_2 from the capture process is purified, compressed and transported to serve as a feedstock for a CO_2 conversion process. However, there has been a recent focus on integrating the capture and conversion reactions in a “reactive carbon capture” process.

Reactive carbon capture (RCC) involves the integration of CO_2 capture and conversion technologies without a separate process step to generate a purified CO_2 intermediate. This eliminates the need to regenerate the capture medium and the need to purify, compress, transport or store the captured CO_2. RCC approaches include integration of CO_2 separation and conversion in one step, integration of separation and conversion in one unit, and process intensification. RCC can utilize CO_2 captured from air or a point source (i.e., power generation and industrial facilities). For the purposes of this meeting, RCC approaches that utilize CO_2 sourced from the ocean are excluded due to their relative novelty compared to RCC integrated with direct air capture (DAC) or CO_2 point sources, but they are recognized as an emerging area of interest.

RCC spans several technology approaches, including thermochemical (including alternative forms of heating), electrochemical, biological and mineralization processes, and can result in products including chemicals, fuels and building materials. **Exhibit 1-1** illustrates the RCC concept. Note that although mineralization is not included as an RCC pathway in Exhibit 1-1, it is included within the U.S. Department of Energy (DOE)/Office of Fossil Energy Management’s (FECM) portfolio of RCC approaches.

RCC offers opportunities to lower energy intensity and reduce capital cost relative to the separate processes of carbon capture and conversion. Illustrative examples of the value proposition of RCC and the reduction in energy requirements and capital cost they enable are summarized elsewhere.[2,3]

Exhibit 1-1. Reactive carbon capture concept[4]



1.2 PREVIOUS ACTIVITIES ON RCC

This meeting built upon previous engagement efforts of the RCC research community. A prior meeting, titled "Reactive CO_2 Capture: Process Integration for the New Carbon Economy," was held at the National Renewable Energy Laboratory (NREL) February 18-19, 2020.[5] A large focus of the meeting was to discuss approaches for merging CO_2 capture and CO_2 conversion or utilization systems into integrated reactive capture strategy, to define the value proposition of

[2] M. Freyman et al. Reactive CO_2 capture: a path forward for process integration in carbon management. (2023). https://doi.org/10.1016/j.joule.2023.03.013.
[3] I. Robinson. The Potential Impact of Combining Carbon Capture and Utilization. ARPA-E Reactive Carbon Capture Workshop. (2022). Workshop | arpa-e.energy.gov.
[4] R. Siegel et al. Reactive Capture of CO_2: Opportunities and Challenges. (2022). https://doi.org/10.1021/acscatal.2c05019.
[5] Summary Report of the Reactive CO_2 Capture: Process Integration for the New Carbon Economy Workshop, February 18–19, 2020 (nrel.gov).

RCC, and to identify a path forward for this emerging field. The Advanced Research Projects Agency-Energy (ARPA-E) also hosted a workshop on RCC in 2022 to identify opportunities and potentially transformational technology approaches for inexpensive conversion of diffuse or point-source CO_2 to high-value chemical intermediates and/or fuel products.[6] Since then, DOE has invested in research and development (R&D) in RCC, including fundamental science and applied R&D, with several lessons learned in the process. The 2024 meeting was held to bring together the RCC community to share these findings and identify R&D needs to further help support the field moving forward.

1.3 Meeting Objectives and Structure

The purpose of the 2024 RCC Project Review Meeting was to bring together the community of industry, university and national lab researchers developing RCC technologies and to share lessons learned from recent DOE-funded projects on RCC, as well as perspectives on progress, technology alternatives, opportunities and research, development and demonstration (RD&D) needs to further advance the field.

Specific goals of the meeting:

1. Understand what has been accomplished in the field of RCC since the first meeting on this topic in February 2020 and review activities within DOE offices on RCC, including the FECM, ARPA-E, the Industrial Efficiency and Decarbonization Office (IEDO), and the Office of Science – Basic Energy Sciences (BES).
2. Understand current challenges, RD&D needs and opportunities in the RCC field.
3. Identify activities needed to scale-up RCC to achieve continuous operation integrated with CO_2 capture from a point source or air.
4. Identify enabling technologies that can help overcome current challenges in the RCC field.
5. Foster collaboration among the RCC community and identify DOE activities needed to advance the field of RCC and support further development.

The agenda for the 2024 RCC Project Review Meeting included introductory remarks from FECM, NREL, ARPA-E and IEDO. The balance of the agenda included individual presentations, panel discussions, and breakout sessions. The agenda can be found in the **Appendix**. This report provides a summary of each session, followed by a summary of findings.

[6] ARPA-E Reactive Carbon Capture Workshop. Workshop | arpa-e.energy.gov.

2 DOE RCC Project Overview Sessions

Objective: To review the status and findings of prior and ongoing federally funded efforts. Specifically, to highlight the technical successes and challenges of unique, independent projects.

The first session comprised a summary of nine DOE-funded FECM field work proposals (FWPs), R&D projects, and work funded by ARPA-E involved in RCC technology development, presented by the project performers. Projects included a range of RCC technologies, including CO_2 to methanol, molten salt systems for CO_2-based oxidative dehydrogenation, electrocatalytic conversion of CO_2 to products, and integrated direct air reactive capture technologies. Presentations are listed in **Exhibit 2-1**.

Exhibit 2-1. DOE-funded RCC projects

Performer	Project Title
Pacific Northwest National Laboratory	Integrated Capture and Conversion of CO_2 into Materials: Pathways for Producing CO-Negative Building Composites and Expanding IC_3M for C_1 and C_2 Production
National Renewable Energy Laboratory	Pressure-Swing Process for Reactive CO_2 Capture and Conversion to Methanol through Precise Control of Co-Located Active Sites in Dual Functional Materials
Lawrence Livermore National Laboratory and National Renewable Energy Laboratory	Direct Air Reactive Capture and Conversion for Utility-Scale Energy Storage
Oak Ridge National Laboratory	Porous Catalytic Polymers for Simultaneous CO_2 Capture and Conversion to Value-added Chemicals
North Carolina State University	Novel Molten Salt System for CO Based Oxidative Dehydrogenation with Integrated Carbon Capture
Circe Bioscience	Circularizing Industries by Raising Carbon Efficiency
Energy Frontier Research Center	Center for Closing the Carbon Cycle (4C)
National Energy Technology Laboratory	Integrating CO_2-Selective Polymer Layers and Electrocatalytic Conversion
University of Delaware	Bioenergy Production Based on an Engineered Mixotrophic Consortium for Enhanced CO_2 Fixation

The DOE-funded R&D projects listed in Exhibit 2-1 discussed various RCC approaches targeted at a range of products.

- Pacific Northwest National Laboratory (PNNL) presented their research on integrated capture and conversion of CO_2 into methanol employing nonaqueous N-(2-ethoxyethyl)-3-morpholinopropan-1-amine (EEMPA) solvents and a second RCC approach focused on producing artificial wood composite filler material (CO_2LIG). This CO_2-negative material can be substituted for up to 90% of the conventional wood composite (high-density polyethylene [HDPE]) at a projected cost lower than HDPE.

- NREL presented the current state of their dual-functional materials research for RCC, along with an analysis of the carbon intensity of methanol production using their process.
- Oak Ridge National Laboratory (ORNL) presented their approach to RCC using porous catalytic polymers and discussed how reactor and heat exchanger design, scale and impurities impact product cost, based on techno-economic analysis (TEA) and life cycle analysis (LCA).
- North Carolina State University presented their oxidative dehydrogenation molten salt process for ethane conversion to ethylene and demonstrated stable performance for 500 RCC cycles. Challenges in catalyst development, how they achieved increased performance, and an analysis on the process variables to prevent side reactions were discussed.
- Circe Bioscience presented their work building custom biocatalysts and reactor design for a pre-pilot prototype of their RCC process. Their biocatalyst and reactor design can produce kilogram quantities of their product targeted for food items.
- University of California at Irvine presented an overview of the work conducted by the Center for Closing the Carbon Cycle (4C), an Energy Frontier Research Center with the goal to advance synergistic capture and conversion of CO_2 from dilute streams into useful products through the convergent study of sorbents and catalysts. Discussions included the use of computational methods for sorbent discovery and experimental validation, methods for high-throughput evaluation of new sorbents, and efforts to establish new descriptors for RCC that include durability.
- NREL presented their research on amine-based materials and dual-functional materials for RCC in a methanation reaction, demonstrating stable cycling performance and process intensification compared to separate CO_2 capture and conversion.
- The National Energy Technology Laboratory (NETL) presented their work integrating CO_2-selective membranes into an electrolyzer device to capture and convert dilute CO_2 to formic acid. The presentation included a discussion on the electrochemistry challenges of incorporating CO_2-selective polymers into electrode architectures and optimizing interfaces. Scale-up issues were also discussed, along with a TEA and LCA on the cost and environmental impact of the RCC approach.
- The University of Delaware presented their work on combining two biochemical CO_2 utilization routes using genetically engineered biological organisms. The microorganisms were engineered to be more selective for CO_2 and are used to convert CO_2 into ethanol and isopropanol. The presentation included a discussion on the methods for improving selectivity to inhibit side reactions.

2.1 Key Findings

This session highlighted a variety of R&D efforts for developing RCC technologies. Some of the key items highlighted by project performers are below, grouped by categories.

- **Fundamental Science Questions and Needs:** RCC opens opportunities for different mechanisms of CO_2 conversion and chemical equilibria to exploit. There is a need for fundamental science — including characterization, spectroscopy and testing — to understand reaction mechanisms, C-speciation at reactive surfaces/catalysts, and new CO_2 reactivities afforded by RCC that can be then leveraged to design improved RCC approaches.

- **Materials and Process Design for RCC:** RCC requires rational materials design that considers the requirements of both CO_2 capture and conversion processes, and co-optimization of materials and processes.
    - For thermal catalytic approaches to RCC, projects highlighted that materials must match capture and reaction conditions, withstand high temperatures, and sustain switches between oxidative and reductive environments. Excellent CO_2 capture materials may not necessarily be good materials for RCC. An example of this is the case of amines, which are widely used as CO_2 capture materials, but exhibit a mismatch between capture and conversion operation windows that makes them unsuitable as RCC materials.
    - For electrochemical approaches to RCC, there are opportunities to translate knowledge from electrochemical CO_2 reduction to reduction of CO_2 in the captured state. High-throughput approaches were highlighted to allow for rapid evaluation of new materials. There is a need to establish descriptors for RCC materials that include various properties (durability, tolerance to impurities) and to co-design sorbents and catalysts. Additional areas of R&D for electrochemical RCC include approaches to lower electrolyzer operating voltages.
    - Process conditions (e.g., cycling times, loading procedures, operating conditions, etc.) impact performance and need to be optimized for RCC processes relative to separate CO_2 capture and conversion.
    - Durability of capture materials, mitigation of impurities in the process, and modes of degradation and deactivation need to be more thoroughly evaluated for RCC systems.
- **Analysis Needs:** A rigorous TEA/LCA framework is needed to identify important metrics for process performance of various RCC approaches and demonstrate the value proposition of RCC.
- **Value Proposition of RCC:** Several projects demonstrated RCC processes can reduce capital expenses, energy requirements and greenhouse gas (GHG) emissions relative to conventional separate carbon capture and conversion and current baseline processes. The value proposition of RCC is in many cases dependent on the availability of low-carbon intensity co-reactants (e.g., green hydrogen [H_2]) and abundant renewable electricity.
- **Technology Advancement and Scale-Up:** The field of RCC has advanced to include a diverse set of technologies at proof-of-concept stage that are ready for maturation to continuous systems, which presents the opportunity for shared learning and collective advancement through coordinated R&D and establishing partnerships between academia, national labs and industry.

3 RCC INDUSTRY TALKS AND PANEL SESSIONS

Objective: To review the status and work that is ongoing on RCC technology in industry and to provide insights in technology development, challenges and next steps in technology commercialization.

3.1 INDUSTRY TALKS

Industry talks on RCC technology were performed during the meeting. The topics were "Reactive Capture of CO_2 for Renewable Methane Production" by Raghubir Gupta (Susteon) and "Algae-based Reactive Carbon Capture Opportunities" by David Hazlebeck (Global Algae).

During this session, Susteon introduced a systems approach for the integration of technologies to achieve their goals in RCC technology. The concept of dual-functional materials was presented, as were their current efforts to create sorbent-catalyst combinations that can capture CO_2 from a point source or DAC and directly convert it into a value-added product. The target products were methane, methanol or other hydrocarbons. In addition, Susteon presented the following technical considerations:

1. How will oxygen (O_2) in the CO_2 stream affect the catalyst?
2. What are the equilibrium limitations of the desired reaction?
3. What is the target product selectivity? What are the necessary reaction conditions (i.e., temperature, pressure)?
4. Is a process design feasible and scalable?

Susteon showed their bench-scale reactor system that can capture and convert 1 kilogram of CO_2 per day to renewable natural gas (RNG). The development and testing of their dual-functional material demonstrated there was some sensitivity to temperature and humidity changes. Humidity significantly improved the sorbent by up to 50% in CO_2 capture capacity when a small amount of water was introduced to the simulated DAC feed. Their system is designed with Joule heating technology, putting the heat source near the sorbent, which reduces the electrical requirement for thermal swing dramatically. The TEA and sensitivity analysis revealed the cost of hydrogen and the cost of electricity were the highest contributors to the cost of producing RNG. Susteon reported their dual-functional material with cyclic direct electric heated methanation is at a Technology Readiness Level (TRL) of 5.

Global Algae reported on their work growing microalgae for animal feed applications. Their R&D effort is focused on product separations and scale-up of the algae system using a raceway pond. The raceway pond allows for greater scalability of the process. The optimal temperature range for algae growth is between 70 and 90°F and can continue operating in the temperature range of 55 to 110°F. Global Algae stated that CO_2 concentration, and therefore CO_2 source, has a significant impact on both productivity rate and cost of algae production.

3.2 Panel 1: Commercialization of RCC Technology — SBIR Program Updates

Objective: The panelists were asked to present their perspectives on the value proposition of RCC compared to capture and conversion as separate processes, along with a summary of their RCC concept and major findings.

In this session, panelists included Sravanth Gadikota from Carbon to Stone, Wei Lu from MoleculeWorks, and Rouzbeh Savary from C-Crete. After each panelist summarized their RCC technology, the audience asked questions of the panel. The session was highlighted by the following key messages:

- Carbon to Stone is working with various cement and steel manufacturers, envisioning closing the carbon loop and slag loop to recover critical materials in slag while decarbonizing. The technical approach is a single-step RCC and is heavily focused on using industrial residues, electric arc finance slag and cement kiln dust for the recovery of valuable minerals. The key considerations for scale-up include managing variance in feedstock compositions (flue gas, alkalinity in the slags), enhancing solvent recyclability and increasing usability of carbonates.
- MoleculeWorks presented a DAC-to-methanol RCC technology intended to reduce three unit operations into one integrated CO_2 capture and electrochemical conversion-to-methanol process to reduce complexity through RCC technology. Their innovation is the integration of mass and heat transfer reactor design with an anodic membrane electrode assembly for their alkaline electrochemical cells. The challenges to this technology are selectivity and conversion to the desired product and the long-term stability of the electrochemical cell.
- C-Crete presented their RCC technology for the pourable carbon-negative concrete industry and provided numerous pictures and video footage using their existing C-Crete technology, including a commercial application using 120 tonnes of concrete in Seattle.

3.3 Panel 2: Enabling Technology — Laboratory-Scale Activities to Advance Reactive Capture

Objective: Panelists were asked to present their perspectives on the advantages of RCC, the target CO_2 source and scale, and any challenges for enabling continuous process integration for RCC systems that are being developed.

In this session, the panelists included Curtis Berlinguette from the University of British Columbia, Surya Prakash from the University Southern California, Greeshma Gadikota from Cornell University, and Douglas Kauffmann from NETL. After each panelist presented the RCC technology for their organization, the audience asked questions of the panel. The session was highlighted by the following key messages:

- Curtis Berlinguette presented their closed-loop integrated RCC system using a bicarbonate electrolyzer. The advantages to this technology are that it is easier to build and operate, is less sensitive to impurities, is not sensitive to O_2, and has higher CO_2

utilization and higher electrolyzer performance when compared to a CO_2 electrolyzer. The challenges include nitrogen oxide (NO_X) sensitivity and high-voltage requirements.

- Surya Prakash presented their concept on a methanol economy, along with multiple pathways for products using RCC. The hydrogenation of CO_2 to methanol, ethylene glycol or methane were noted as potential conversion pathways. Their RCC technology is based on a tertiary-amine ionic liquid coupled with a transition metal catalyst, which promotes both capture and conversion of CO_2.
- Greeshma Gadikota presented their vision for coupling RCC with resource recovery and discussed carbon mineralization. They also discussed different environmentally benign solvents for regenerating solid carbonates and resource recovery through development of an electrochemical pathway to regenerate solid carbonates and concentrate CO_2. A challenge with carbon mineralization technology is that the mineralization process is approximately 12 hours or longer compared to faster amine-based capture methods. In addition, process integration is dependent upon the composition of the alkaline industrial residues.
- Doug Kauffman presented work focused on microwave and electrochemistry-based RCC technology. Efforts are ongoing to develop bifunctional materials for RCC to natural gas. The microwave RCC technology utilizes a metal oxide sorbent for DAC and uses the carbonate-metal oxide to produce carbon monoxide followed by hydrolysis to manufacture other products for sustainable chemicals. Their bench-scale studies are focused on optimizing active material composition, achieving relevant form factors, understanding deactivation, and scaling.

3.4 Panel 3: Reactive Capture in Industry — Opportunities for Reactive Capture Integration with DAC and Point-Source Capture

Objective: Panelists were asked to present their perspectives on the type of carbon conversion processes currently being pursued and how RCC fits in, opportunities and challenges of RCC, and market potential for RCC.

In this session, the panelists included Todd Wilke from Carbon Engineering, Josh Wicks from Twelve, and Gaurav Sant from CarbonBuilt. The panel identified several opportunities and challenges for the application of RCC. Following the panel discussion, the audience asked questions of the panel.

- Carbon Engineering discussed their commercial DAC plant design and the challenges for RCC due to variable input for regeneration and conversion. The DAC capture rate continuously changes due to environmental conditions; non-process elements such as emissions and contaminants can vary and the source of fuel may also change. There was a large emphasis on prolonged pilot testing to evaluate possible changes in RCC performance under realistic process environments. A significant challenge is determining the most cost-effective products to focus on. It was highlighted that the product will compete with other technologies, that sources of CO_2 make a difference, and that the cost of the overall process all play a part in the profitability. Additional emphasis was placed on the effect of particulates on the process and solvent materials.

- Twelve presented their work to evaluate the potential for utilizing CO_2 to products, such as their CO2Made® aviation fuel. Their process for CO_2 conversion to jet fuel includes two electrolyzers using the Fischer-Tropsch reaction to upgrade the syngas to jet fuel. Twelve is currently using electrolyzer stacks and larger cells for scaling the process. The potential opportunity for RCC is to couple with DAC technology, since this decouples the CO_2 point source, allowing for deployment of the technology into areas not otherwise possible.
- CarbonBuilt focused upon materials that reduce the embodied carbon of their concrete products by 70% to 100% with no compromise in price, performance or plant operations. They emphasized the need for consistency and constancy in the cement industry, and looked to develop a process that replaces the natural gas boiler for steam production. Using this novel design, they were able to achieve 71% reduction in carbon footprint.

4 BREAKOUT SESSIONS

In the breakout sessions of Day 2, the moderators encouraged the audience to engage in discussions around three topics:

- Topic 1: RCC Research Questions
- Topic 2: RCC Market Pull Scenarios
- Topic 3: Path Forward and Fostering Collaboration in the RCC Community

To promote interaction between the participants, breakout sessions were divided into three small preselected groups to encourage diversity across national labs, academia and industry. Each group had 25 minutes of discussion on the specific topic before rotating to the second and then the third topic. The audience was asked to submit answers to session topic questions; at the front of the discussion room, there were three white boards for participants to provide keywords for three topics: the vision, the key opportunities and the priority actions. In the breakout sessions, the attendees used sticky notes to provide keywords and colored sticky notes to rank the importance of each keyword.

The summary of the facilitated discussions acts as an introduction to the breakout sessions and is detailed hereafter.

4.1 TOPIC 1: RESEARCH QUESTIONS IN RCC

The breakout room participants were asked to submit ideas for the session topic "Research Questions in RCC," and to provide their vision, key opportunities and priority actions related to the session topic.

4.1.1 Vision

Participants were asked to provide, in one word or a short phrase, their vision in relation to the research questions they have on RCC. Participants began by emphasizing the multidisciplinary approach in materials and process development for RCC. The following points summarize the major suggestions:

- Balance the funding for R&D on RCC approaches from proof of concept to integrated systems.
- Conduct analyses to provide a thorough understanding of the energy efficiency and carbon efficiency of proposed RCC processes.
- Study reactivity, stability/durability and degradation of the capture and conversion materials under conditions that simulate real RCC process operation, including realistic CO_2 concentrations, O_2 concentrations, and impurities.
- Characterization of the feedstock(s) for RCC processes, as the quality of feedstock and/or sources of CO_2, can affect the product and process costs, performance and product yields.
- Process intensification, including product separation, needs to be considered at the beginning of the process development phase. Need to think early on about the integrated process for co-generation of products from low-concentration sources and

possible optimization routes.
- Need to show the market value of the product and the low-carbon footprint of the process using both TEA and LCA.

4.1.2 Key Opportunities/Actions

Participants provided input for key opportunities and actions and discussed the following topics on RD&D for RCC technology:

- RCC testing with real CO_2 sources (i.e., point sources or DAC) for long-term durability is needed. Interest in testing prototype systems in real operating environments at smaller scale.
- Co-optimization of materials and processes for RCC, including considerations, such as new CO_2 reactivities, new materials, catalysts, understanding mechanisms, impact of impurities, matching capture and conversion rates, etc.
- Further research on regeneration of new reactive capture materials.
- Testing of RCC components in integrated systems. While CO_2 capture and conversion technology may be mature, their integration in an RCC system lowers the TRL and understanding of the system's physical properties.
- Use of artificial intelligence (AI) and machine learning (ML) systems to design RCC processes and co-optimize materials and processes.
- Evaluation of potential opportunities for using RCC in upstream processes, such as precombustion CO_2 capture applications.
- Research alternative feedstocks and hybrid approaches as a pathway to reduce reliance on green hydrogen and electricity for RCC processes.
- Development of materials, processes and conditions to optimize the RCC process by matching CO_2 capture and conversion rates.
- Conduct TEA and LCA, starting at early stages in the design and conceptualization of RCC processes, to determine under what conditions RCC is advantageous. The level of detail of the TEA and LCA needs to also be proportional to the TRL level (i.e., a "back of the envelope" type of TEA/LCA with sensitivity analyses at low TRL as compared to the full analysis at higher TRL). TEA and LCA evaluation protocols are needed for RCC technology, such as establishing standard metrics and goals to demonstrate the value proposition for RCC research.
- Reevaluate old technology with RCC in mind and look at how various processes could be redesigned (i.e., DAC).
- Collaboration with industry partners to identify innovation and R&D needs in RCC.
- Efforts on advanced manufacturing of RCC components (e.g., membrane materials, interfacial structures) and development of tools and methodologies to scale-up RCC processes, including modular approaches.
- Two RCC topics to prioritize are CO_2-to-organics and CO_2-to-inorganics. Applied R&D efforts should focus on de-risking existing technologies and identifying promising pathways.
- A roadmap is needed to access the integration capabilities and use this to develop RCC

hubs that can focus on the most promising reaction pathways. Hubs will help scale-up of the RCC technology from the lab scale.

- Development of modular and dynamic systems that can deal with intermittency, and how intermittency effects the RCC process (integration of grid and renewables).
- Multidisciplinary analysis efforts, including international groups. Bringing in experts with other backgrounds may help diversify perspectives on RCC. Some of these RCC technologies may be better for exporting as opposed to using domestically. Efforts should also be focused on thinking outside of the box to inspire novel RCC materials and processes.
- Data management: Discussion included how to properly manage the data for presentation for funding and moving the project forward, including data management, data sharing, and AI/ML integration. There are differences in how academia and industry each understand data management and their rights to data management. A data hub that is specific to RCC data was suggested.

Exhibit 4-1. Topic 1 priority actions

Attendees identified the concepts that have the highest priority for "Research Questions in RCC." The top three priority topics identified by each group:
Priority 1
Co-optimization of materials and processes.
Set standard metrics and goals and demonstrate the value proposition of RCC.
Develop modular plus dynamic systems that can deal with intermittency.
Priority 2
Integration (testing) with real CO_2 sources (point source or DAC) under real conditions.
Rethink/reassess existing capture and conversion processes for RCC.
Analysis efforts (TEA/LCA) that are more rigorous at higher TRL, with sensitivity analysis focus at lower TRL.
Priority 3
Design new reactivity around CO_2 (novel materials, catalysts).
Diversify the product portfolio for RCC.
Explore a broad range of RCC approaches using CO_2 from DAC or flue gas from industrial or power generation facilities.
Coordinated DOE pipeline from TRL 1 to TRL 9.

4.2 Topic 2: Market Pull Scenarios for Reactive Capture

The breakout room participants were asked to submit ideas for the session topic "Market Pull Scenarios for Reactive Capture," and to provide their vision, key opportunities and priority actions related to the session topic.

4.2.1 Vision

Participants were asked to provide, in one word or a short phrase, a vision for market pull scenarios and made the following recommendations:

- A focus should be on decreasing the cost of RCC by reducing both capital expenditures (CAPEX) and operating expenses (OPEX).
- Efforts in educating the public about the importance of RCC to encourage public acceptance.
- DOE can facilitate the path to commercialization by moving RCC technology from concept to pilot scale.
- Provide a prospective roadmap, including all relevant DOE offices, of funding toward increasing the TRL of RCC technologies.
- Incentivize corporate partnerships to advance new technology to market.
- Work should begin to develop policy incentives for RCC technologies while at an early stage, including policies to support a broader spectrum of CO_2 conversion commodities and products, not just fuels. Policy incentives could be combined with sensible commercialization and business models for products enabling scaling and deployment with long-term goals of scale and decarbonization impact.
- Need for clarity on long-term policy positions and additional funding as the technology matures.
- DOE should facilitate collaboration between CO_2 producers, RCC technology developers and end users of RCC products, so that there is a clear path that works economically.
- There needs to be cost-competitive products, so that there is no additional cost for products derived from RCC technologies.
- DOE should support development of on-site RCC units where CO_2 and all infrastructure are available at that site.

4.2.2 Key Opportunities/Actions

Participants provided input for the key opportunities and actions and emphasized cost versus scalability. Most of the RCC technology is at TRL 2-4 and need funding for scale-up R&D, along with funding for new R&D ideas. Participants made the following recommendations:

- A “shotgun approach” to fund novel ideas, which may turn out to be successful and provide new commercial opportunities.
- Cost-share requirements and funding limits are a barrier to innovation. The Small Business Innovation Research (SBIR) program does not require cost share, but funding is too low for national lab work. Reducing financial assistance cost share below 20% would help remove barriers for small businesses.
- Improved synchronization of the funding timeline between the slower-moving grant cycle compared to the fast-moving R&D timeframe of startups.

- Energy technology timeframes are long compared to some other technologies. Need a pipeline from TRL 1 to TRL 9 with coordination between funding bodies and clear delineation of boundaries between technologies, products and/or TRL levels.
- Develop funding-promoted collaborations, including with off-takers of primary RCC products, such as "RCC Clean Fuels" or customers who are willing to be primary purchasers of RCC products.
- Possible DOE support for public education regarding RCC products. Development of basic carbon capture and storage (CCS)/chemical terminology with an environmental product declaration may help with public awareness and acceptance.
- At a later stage, a green products certification could help with public adoption of products.

Some participants suggested that RCC should be focused on carbon dioxide removal (CDR) with a higher priority so that the technology could be made available anywhere. The challenge may be the financial feasibility of DAC for RCC. Another option for RCC may be to integrate with industrial and power generation sources due to the heat source availability.

There is a need to study all the RCC product options for the market. Participants suggested that DOE guidance on products, both positive and negative, with margin considerations would be beneficial. An analysis of market size and impact for sectors/industries reveals approximately 20% of products (ethanol and ethylene) account for 80% of the market according to the Advanced Manufacturing Office [AMO] chemical product list). Participants highlighted the need to have an active study on petrochemical products market in relation to possible RCC products.

In the discussion on customer willingness to pay a premium for low-carbon products, the following questions were asked:

- Would the customer be willing to pay a premium in the short term? There is a need to understand the customer needs and perspective and to ensure that the RCC products are less expensive than the conventional options.
- How to account for change in the price over time of fossil-based conventional products?
- How to find products and local markets to eliminate the need for transportation?
- How can RCC technologies be tailored to manufacture products without the need for further purification?
- Is there a way to show value of long-lived products versus short-lived products that do not abate CO_2 in the long term?

Exhibit 4-2. Topic 2 priority actions

Attendees identified the concepts that have the highest priority for "Market Pull Scenarios for Reactive Capture." The top three priority topics identified by each group:
Priority 1
Funding "shotgun approach" on R&D ideas.

Attendees identified the concepts that have the highest priority for "Market Pull Scenarios for Reactive Capture." The top three priority topics identified by each group:
DOE guidance on products, both positive and negative, with margin considerations.
DOE support on public education regarding RCC products.
Priority 2
Focus R&D on RCC scalability.
DOE support for innovation.
Collaborate with off-takers of primary RCC products.
Priority 3
Customer engagement/education.
Bring policy into R&D process and understand implications to product and technology options.
Coordinated DOE pipeline from TRL 1 to TRL 9.

4.3 Topic 3: Path Forward and Fostering Collaboration in the RCC Community

The breakout room participants were asked to submit ideas for the session topic "Path Forward and Fostering Collaboration in the RCC Community," and to provide their vision, key opportunities and priority actions related to the session topic.

4.3.1 Vision

Participants were asked to provide, in one word or a short phrase, their vision in relation to the path forward and fostering collaboration in the RCC community and made the following recommendations:

- Energetic and dynamic community that is composed of multidisciplinary teams, which include academia, national labs and industry, along with collaboration between BES/early fundamentals and the applied labs.
- Federal, industry, academia and lab collaboration that focuses upon a systems approach for RCC.
- Development of a "Carbon Matchmaker" tool for RCC and industry where DOE provides targeted topical information on existing and emerging capabilities of key DOE partners.
- Provide RCC technology developers with cost-free cooperative research and development agreement (CRADA) lab vouchers (for lab expertise) and provide easy access to lab capabilities.
- Need global collaboration, local application ("Think Global, Act Local").
- Development of an RCC hub that focuses on the intensification and integration of technology related to capture and conversion industries and the product value.

Participants would also like to have a roadmap for stakeholders for RCC. Additionally, participants highlighted the need for easier access to testing facilities, ability to leverage national lab facilities, access to government-supported large-scale testbeds, DOE-funded applied centers, and a knowledge base for understanding the capabilities of each lab and their typical work arrangements. These capabilities would enable multiple deployment routes, such as the simultaneous development of emerging technologies with pilots and demos at multiple scales and sites.

The need for more frequent meetings and workshops where all stakeholders can be involved for greater collaboration was also highlighted. Integration with downstream consumers and understanding industry-driven science research with collaboration with international expertise and a government-facilitated exchange international collaboration initiatives. Need more industry partners that provide access to reactants such as flue/off gas.

4.3.2 Key Opportunities/Actions

Participants made the following recommendations:

- Need for fast-track access to R&D facilities, such as national labs facilities, to help small startup companies. Participants highlighted that it takes a lot of time and resources for small companies to engage national labs. Vouchers could be an option or directed funding such as in a CRADA. Participants highlighted the needs for a simplified way of accessing national lab capabilities.
- Better access to aspects of commercial technology for pilot testing. Participants highlighted the need to streamline access to pre-pilot testbeds, and then help gain access to commercial technology to help early evaluation of low-TRL technologies. This may help lower risk by replication of data across multiple locations and technology devices. Access to the National Carbon Capture Center (NCCC) would be helpful.
- Need to set practical targets for minimum viable product and scale-up. Participants emphasized that too much time is often spent at the bench, not enough time is spent in scale-up. For example, create capture and conversion teams at RCC hubs to ensure integration by including expertise on both capture and conversion.

There were discussions on industry engagement and the following points were noted:

- Need to provide industry engagement on a regular basis.
- Need to build a fact sheet for the capabilities of the DOE facilities, national labs and DOE partners. Indicate the test facility, capabilities of testing and characterization capabilities.
- Need for education and training on TEA and LCA development for technology developers to get the tools into the hands of those who are not TEA experts (i.e., experimentalists). Facilitate collaborations between researchers and national laboratories with analysis capabilities to conduct assessments.
- Recommendation for DOE to provide “preferred vendors” for fabrication of materials. Participants highlighted that there is difficulty of not being able to use DOE funding for foreign suppliers, test sites, researchers and labs. DOE requires the use of U.S. facilities.

The "Buy American – Build American" restricts purchases at lower TRL levels. A preferred list of fabricators would help to eliminate this difficulty.

- Need to facilitate establishing scale-up partnerships between technology developers and industry partners that specialize in scalability. Establishment of a multi-lab consortium would help to facilitate progress towards common goals.
- Need to fund an analysis effort to identify technology-agnostic targets based on TRL and business model to identify most promising products to target via RCC and prioritize these. This would enable companies to know what direction to move towards.
- Need to align RCC effort across DOE offices to provide coordinated multi-office funding, address TRL gaps and prevent duplication of efforts across multiple DOE offices.
- Recommendation for DOE to host multidisciplinary workshops and conferences structured around RCC topics and provide postings earlier. Participants thought the RCC workshop could be turned into a conference setting with larger number of people, more information and more networking opportunities. This would foster collaboration. Deeper collaboration could be encouraged through database and knowledge-sharing at conferences.
- DOE can encourage collaboration by including stipulations in funding opportunity announcements (FOAs; i.e., including industrial partners).

Exhibit 4-3. Topic 3 priority actions

Attendees identified the concepts that have the highest priority for "Path Forward and Fostering Collaboration in the RCC Community." The top three priority topics identified by each group:
Priority 1
Align offices for RCC R&D.
Fast track access to researchers/national labs for small startups.
Priority 2
Set practical targets: minimum viable product and scale-up.
Establish a multilab consortium.
Create capture/conversion teams at the hubs.
Priority 3
Fund a large consortium.
Benchmarking/standard set of testing.
Facilitate scale-up partnerships.

5 RCC PROGRESSION SINCE 2020

This meeting highlighted the clear progress that has been made in the RCC field and presented a significant amount of learnings that were generated because of DOE's investment in the space following the 2020 RCC meeting. RCC moved from largely a concept in 2020 to a reality in 2024. Albeit mostly at an early TRL stage, many learnings — both on opportunities and challenges — have already resulted from DOE's investment in the space. **Exhibit 5-1** provides a summary of progress that has been made since 2020 on various aspects related to RCC.

Although there has been a clear progression on many aspects of RCC development, several challenges that were identified in 2020 remain important. The prior meeting highlighted the scale-up challenge. Although this challenge remains in 2024, RCC technologies can now leverage ongoing learnings from standalone CO_2 conversion systems (e.g., biological CO_2 reactors, CO_2 electrolyzers and thermal catalytic reactors) on their path to scale-up. Another example is the challenge of available low-carbon power, which is increasingly clear in 2024. Many RCC technologies will require low-carbon energy and clean hydrogen, which are both precious commodities for the foreseeable future. This may result in a competition between RCC and other technologies that also require low-carbon energy (e.g., traditional carbon conversion processes and DAC) or clean hydrogen (e.g., traditional carbon conversion technologies or power applications).

Overall, although the field of RCC is still just emerging, it is becoming increasingly more apparent that to decarbonize the globe, multiple technologies of various scales will be needed. DOE and all of those conducting RCC research should continue to move the RCC area forward in the future.

Exhibit 5-1. Summary of progression of RCC from 2020 to 2024

	2020 Meeting	2024 Meeting
Meeting Focus	• Contextualizing RCC within the carbon management landscape. • Brainstorming approaches for merging CO_2 capture and CO_2 conversion into RCC systems. • Defining nomenclature and the value proposition of RCC. • Establishing a path forward for RCC.	• Reviewing learnings generated from DOE investment in the RCC space following the 2020 meeting. • Understanding remaining challenges, R&D needs and opportunities in RCC. • Identifying activities needed to scale-up and advance the TRL of RCC processes. • Identifying opportunities for DOE to promote collaborations and advance the field of RCC.
Technology Readiness Level (TRL) of RCC Technologies	Mostly TRL 1-2, with a few technologies at TRL 3.	Mostly TRL 3, with a few technologies at TRL 4.

	2020 Meeting	2024 Meeting
DOE Office Engagement	FECM primary DOE office focused on RCC.	Multiple offices within DOE have both an interest and a role to play with regard to funding RCC research.
CO_2 Source for RCC Processes	Focus primarily on RCC integrated with point-source CO_2 capture.	RCC portfolio expanded to include CO_2 from DAC. This addresses a critical challenge of RCC — the scale mismatch of CO_2 generation from point sources and the amount of CO_2 input that RCC applications require. RCC technology integrated with DAC can also remove the need for pipeline transport and geologic storage, which has become increasingly valuable as challenges of obtaining access to pipelines and geologic storage have become evident since 2020.
Policy Support and Available Markets for RCC Technologies	Limited policy support and available markets for RCC products.	• Increased policy support for decarbonization initiatives, including areas relevant to RCC (e.g., BIL $300 million for carbon utilization procurement grants), but continued need for expanded support. • Expanded customer base for lower- carbon RCC products. • Emerging market opportunities, like the co-location of DAC-generated CO_2 with utilization markets.

6 Next Steps for DOE to Advance RCC

Combining the status of the field with the direct feedback from meeting participants, the next steps for DOE — and specifically FECM — in the RCC area may include:

- Holding high-level strategy meetings with ARPA-E, the Bioenergy Technologies Office (BETO), IEDO and BES to outline the various office roles and funding amounts for the RCC area for the near-, mid- and long-term. This is a necessary step since multiple offices within DOE are funding RCC, and alignment would ensure that TRL gaps in RCC technologies are addressed and that efforts are coordinated to advance technology development and avoid duplication.
- Following meetings with other DOE offices, the agency may decide to write a roadmap, or at a minimum a strategic plan, for RCC. A strategic plan mapping how to facilitate the advancements of RCC technologies up the TRL ladder to get to scale-up is valuable because much discussion regarding scale-up and piloting of RCC technologies occurred in this meeting and it appears to be a significant challenge.
- Discussion of more RCC meetings occurred. DOE may consider another meeting in FY24 or FY25 at a larger venue where participation will not be limited.
- In addition to a broader, multiday meeting as a follow-up to this one, there were suggestions that DOE could help the RCC community by hosting targeted meetings (e.g., LCA or TEA) that have a specific focus on RCC.
- DOE, through multiple offices, can continue providing funding in this space through various mechanisms, including lab calls, SBIRs and FOAs.
- As RCC technologies advance in TRL, there is a need to demonstrate performance in operating environments that more closely simulate real process conditions, highlighted as one of the key actions during the meeting. Thus, future DOE funding opportunities should include testing RCC technologies in simulated operating environments, and, as RCC technologies mature, in real operating environments, including RCC pilots in test centers.
- DOE may support future efforts to increase collaboration in the RCC area (e.g., the development of an RCC consortium, including engagement from academia, industry and multiple national laboratories with diverse capabilities; or development of an RCC hub bringing together expertise from carbon capture and conversion areas to facilitate scale-up).
- DOE has valuable systems analysis and computational simulation analysis that could be applied specifically to RCC versus carbon capture and conversion as separate processes. Conducting TEA and LCA starting early in the conceptualization of RCC processes was highlighted as a key opportunity by participants. Thus, DOE analysis groups can begin to develop performance metrics and/or program goals for RCC and support researchers and technology developers in evaluation of RCC approaches.

APPENDIX: MEETING AGENDA

Reactive Carbon Capture Project Review Meeting

National Renewable Energy Laboratory

Golden, CO

January 17-18, 2024

Day 1: January 17, 2024

8:00 – 8:45 a.m. **Check-In and Registration**

8:45 – 9:00 a.m. **Meeting Objectives and Deliverables**

Dan Hancu (U.S. Department of Energy [DOE]-Fossil Energy and Carbon Management [FECM])

9:00 – 9:30 a.m. **State of the Knowledge: Reactive Capture Overview, Challenges, Opportunities**

Joshua Schaidle (National Renewable Energy Laboratory [NREL])

9:30 – 10:45 a.m. **Overview Reactive Capture Activities Across DOE**

Moderator: Ron Munson (National Energy Technology Laboratory [NETL])

9:30 – 9:45 a.m. FECM Activities

Dan Hancu (DOE-FECM)

9:45 – 10:00 a.m. Advanced Research Projects Agency-Energy Activities

Jack Lewnard

10:00 – 10:15 a.m. Industrial Efficiency & Decarbonization Office Activities

Paul Majsztrik

10:15 – 10:35 a.m. Q&A

10:35 – 11:00 a.m. **Refreshment Break**

11:00 a.m. – 12:15 p.m. **Current DOE Projects on Reactive Capture Part 1**

Moderator: Andrew Jones (NETL)

1. Integrated Capture and Conversion of CO_2 into Materials: Pathways for Producing CO-Negative Building Composites (FWP-78606) and Expanding IC_3M for C_1 and C_2 Production (FWP-80562).

   David Heldebrant (Pacific Northwest National Laboratory)

2. A Pressure-Swing Process for Reactive CO_2 Capture and Conversion to Methanol through Precise Control of Co-Located Active Sites in Dual

Functional Materials

(FWP-FY21-RCC-LAB-CALL).

Anh To (NREL)

3. Porous Catalytic Polymers for Simultaneous CO_2 Capture and Conversion to Value-added Chemicals (FWP-FEAA421-FY22).

   Michelle K. Kidder (Oak Ridge National Laboratory)

4. A Novel Molten Salt System for CO Based Oxidative Dehydrogenation with Integrated Carbon Capture (FE0031918).

   Fanxing Li (North Carolina State University)

5. Circularizing Industries by Raising Carbon Efficiency (Advanced Research Projects Agency-Energy [ARPA-E] ECOSynBio Program).

   Marika Ziesack (Circe Bioscience)

12:15 – 1:15 p.m. **Lunch**

1:15 – 1:45 p.m. **Industry Talk Reactive Capture Technology — Reactive Capture of CO_2 for Renewable Methane Production**

Raghubir Gupta (Susteon)

1:45 – 2:45 p.m. **Panel 1: Commercialization of Reactive Capture Technology — Small Business Innovation Research (SBIR) Program Updates**

Moderator: Dylan Leary (NETL)

Sravanth Gadikota (Carbon to Stone), Anna Douglas (SkyNano), Wei Lu (MoleculeWorks), Rouzbeh Savary (C-Crete)

2:45 – 3:00 p.m. **Refreshment Break**

3:00 – 3:30 p.m. **Industry Talk Reactive Capture Technology, *Title TBD***

David Hazlebeck (Global Algae)

3:30 – 4:30 p.m. **Panel 2: Enabling Technology — Laboratory-Scale Activities to Advance Reactive Capture**

Moderator: Sara Hamilton (DOE)

Curtis Berlinguette (University of British Columbia), Surya Prakash (University Southern California), Greeshma Gadikota (Cornell University), Douglas Kauffmann (NETL)

Day 2: January 18, 2024

8:00 – 8:30 a.m. **Check-In and Registration**

8:30 – 9:30 a.m. **Current DOE Projects on Reactive Capture Part 2**

Moderator: Joseph Stoffa (NETL)

1. Center for Closing the Carbon Cycle (4C) Energy Frontier Research Center.

   Chris Hahn (Lawrence Livermore National Laboratory), Jenny Yang (UC Irvine)

2. Direct Air Reactive Capture and Conversion for Utility-Scale Energy Storage (FWP-FEW0277).

   Matthew Yung (NREL)

3. Integrating CO_2-Selective Polymer Layers and Electrocatalytic Conversion (FWP-1022482).

   Douglas Kauffman (NETL)

4. Bioenergy Production Based on an Engineered Mixotrophic Consortium for Enhanced CO_2 Fixation (ARPA-E ECOSynBio Program)

   Hyeongmin Seo (University of Delaware)

9:30 – 10:20 a.m. **Panel 3: Reactive Capture in Industry — Opportunities for Reactive Capture Integration with Direct Air Capture and Point-Source Capture**

Moderator: Lynn Brickett (KeyLogic)

Todd Wilke (Carbon Engineering), Josh Wicks (Twelve), and Gaurav Sant (CarbonBuilt)

10:20 – 10:30 a.m. **Breakout Room Introduction and Ground Rules**

Ron Munson (NETL)

10:30 – 10:45 a.m. **Refreshment Break and Organize into Breakout Rooms**

10:45 a.m. – 12:45 p.m. **Breakout Rooms Discussion**

12:45 – 1:00 p.m. **Concluding Remarks**

1:00 p.m. **Lunch and Adjourn**

2:00 – 3:30 p.m. **Tour of NREL Facilities *(Optional, 30 slots)***