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RENEWABLE ENERGY

Rewiring the Carbon Economy: Engineered Carbon Reduction Listening Day

Summary Report

February 2018

Summary Report from the July 8, 2017

Rewiring the Carbon Economy: Engineered Carbon Reduction Listening Day in La Jolla, California

Listening Day and Summary Report Sponsored by the U.S. Department of Energy

Office of Energy Efficiency and Renewable Energy

Bioenergy Technologies Office

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Foreword

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) invests in a diverse portfolio of technologies to ensure domestic energy security, continued economic competitiveness, environmental sustainability, and the availability of cleaner fuels and power.

This report summarizes the input received from attendees of a public workshop sponsored by DOE-EERE in La Jolla, California, on July 8, 2017. The views and opinions of the workshop attendees, as summarized in this document, do not necessarily reflect those of the U.S. government or any agency thereof, nor do their employees make any warranty, expressed or implied, or assume any liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe upon privately owned rights.

The authors would like to thank Stephen Mayfield and the University of California San Diego for their assistance in organizing and hosting this Listening Day. The authors also acknowledge Ahmad Mia, Brendan Scott, and Colleen Tomaino for their support in planning and administering the event.

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Introduction

On July 8, 2017, the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy's (EERE's) Bioenergy Technologies Office (BETO, or the Office) hosted the Engineered Carbon Reduction: Advanced Strategies to Bypass Land Use for the Emerging Bioeconomy Listening Day (Engineered Carbon Reduction Listening Day) in La Jolla, California. The objective of this listening day was to discuss research and development (R&D) related to non-photosynthetic (i.e., engineered) carbon reduction and valorization pathways that may leverage low-cost electricity. Experts in emerging technology areas, including carbon dioxide (CO_2) capture, chemical reduction, and upgrading, shared their perspective with DOE about the technical barriers and the potential environmental and economic benefits of utilizing waste CO_2 as a primary input for synthesizing fuels and products without photosynthesis.

During morning plenary sessions, eight leading researchers gave presentations on cutting-edge technologies and engineered systems. During afternoon breakout sessions, workshop attendees representing industry, national laboratories, government agencies, research institutions, and universities provided their perspectives on structural, economic, and technical challenges associated with the current state of non-photosynthetic carbon utilization and management technologies. Stakeholders also offered insights on R&D opportunities and needs, as well as the broader economic, societal, and environmental implications for deploying non-photosynthetic CO_2 utilization systems at scale. Figure 1 illustrates the affiliation of the 48 listening day attendees.

This report will provide an overview of engineered carbon reduction, as well as a summary of stakeholder input provided during the listening day. The stakeholder input section starts with carbon capture considerations, followed by stakeholder input on the challenges, opportunities, and needs related to the following topics:

- Non-photosynthetic biological carbon reduction
- Non-biological carbon reduction
- Non-photosynthetic biological upgrading of intermediates
- Non-biological upgrading of intermediates
- Techno-economics, life-cycle analysis (LCA), and supply chain sustainability analysis.

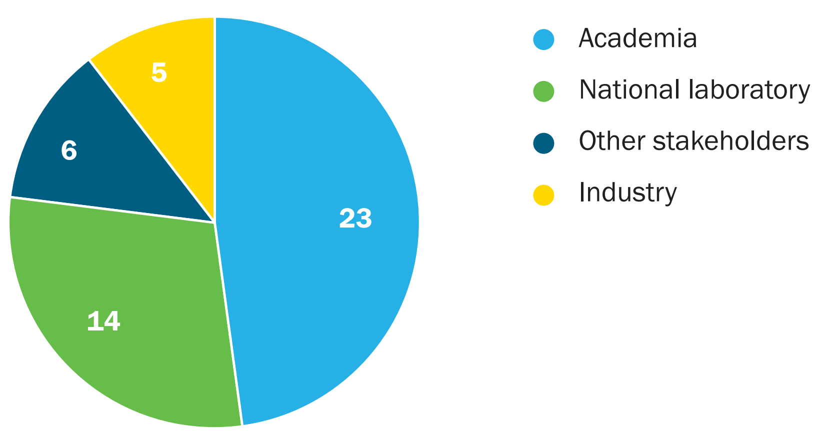

Figure 1. Engineered Carbon Reduction Listening Day attendee affiliation. The attendees identified as "other stakeholders" included individuals who did not identify affiliation and representatives from technical journals, nonprofit organizations, and other research organizations.

Purpose of the Listening Day

BETO supports early-stage applied R&D for technologies and processes to support domestic production of biofuels, bioproducts, and biopower. More broadly, BETO seeks to enable the emergence of a vibrant bioeconomy to provide renewable carbon for a growing and sustainable carbon-based economy; to offer unique ecosystem services that maintain and protect air, water, and land resources; and to create and sustain new domestic jobs throughout the new carbon economy.

A combination of simultaneous advancements has created an opportunity to develop novel waste carbon valorization strategies capable of addressing challenges facing our economy and society. These relevant trends include (1) decreasing electricity costs, (2) continuing reductions in the carbon intensity of available electricity, (3) electrical grid modernization, (4) carbon capture and utilization/sequestration deployment, and (5) advances in conversion technologies, including catalysis, bioengineering, and electrochemical cells.

BETO held the listening day to better understand how the bioeconomy, the concept of engineered carbon reduction, and the trends in carbon capture and electrical grid modernization could intersect. Carbon is the backbone of the modern global economy, as it is a major component of most materials and fuels. BETO has strong expertise in the upgrading and manipulation of a variety of organic molecules to a broad array of valuable chemicals, products, and fuels. Thus far, renewable feedstocks have been largely limited to terrestrial biomass and associated intermediates—which have inherent land and water requirements—and generally have not directly included CO_2. Therefore, BETO is interested in exploring engineered carbon reduction technologies and strategies and in understanding how the economy could be "rewired" to enable a new renewable carbon economy that can better provide for future sustainable energy, material, and environmental needs.

Topic Overview

The potential economic and environmental benefits associated with carbon capture and utilization (CCU) are distinct prospects for DOE's research funding. Direct utilization of waste CO_2 would not only reduce the environmental impact of energy production, but it would incentivize carbon efficiency and monetize cheap and abundant carbon resources. There have been recent commercial-scale carbon capture successes, such as the DOE-supported Petra Nova project in Texas[1] and the Archer Daniels Midland geological sequestration project in Illinois[2]; along with this development, the rapid deployment of renewable power and widespread availability of low-cost electricity imply that electricity will be clean, plentiful, and inexpensive. By leveraging cheap electricity and waste sources of CO_2, the stage has been set for innovative technologies that can leverage electricity to power carbon reduction and upgrading to fuels, chemicals, materials, and other products. DOE and BETO are uniquely equipped to study and enable this technology space.

This section provides an overview of this broad, interdisciplinary concept, including relevant topics such as systems engineering, carbon capture and sequestration (CCS), renewable energy development, and implications for both the emerging bio- and new carbon economies.

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1 "DOE-Supported CO_2-Capture Project Hits Major Milestone: 4 Million Metric Tons," U.S. Department of Energy, Office of Fossil Energy, October 11, 2017, https://www.energy.gov/fe/articles/doe-supported-co2-capture-project-hits-major-milestone-4-million-metric-tons.

2 "Archer Daniels Midland Illinois ICCS Project," U.S. Department of Energy, Office of Fossil Energy, https://energy.gov/fe/archer-daniels-midland-company.

Systems Engineering

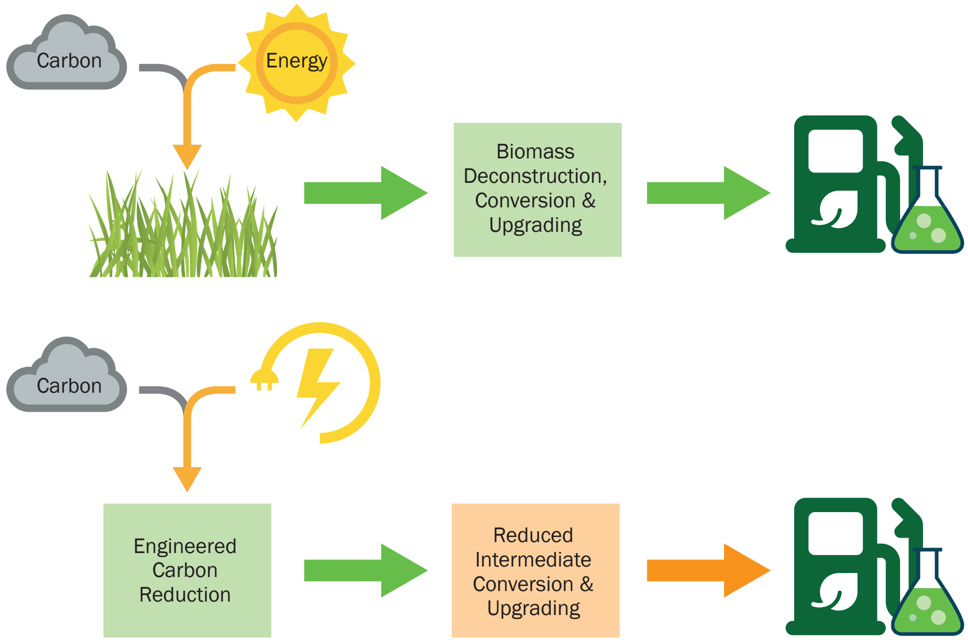


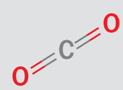
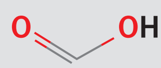
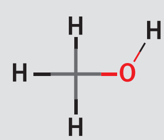
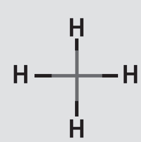
Figure 2. Engineered carbon reduction. As opposed to traditional carbon flows through the biomass supply chain (A), "rewiring" the carbon cycle allows electricity to power CO_2 reduction to bypass land-use requirements as well as biomass generation and deconstruction (B).

As the U.S. economy grows, there is an opportunity to obtain more of its needed carbon—which serves as the backbone for fuels, chemicals and materials—from renewable sources, which will enable a future economy to be capable of serving as a tool for managing carbon. Traditionally, the production of renewable fuels and products has relied on biomass, and this renewable carbon feedstock has been largely limited to terrestrial biomass and associated intermediates, all of which have inherent land and water requirements. Plants use solar energy to convert atmospheric CO_2 into complex organic oligomers. Biomass feedstock is then collected and deconstructed into simple intermediates (sugar, syngas, oil, etc.) before being upgraded to fuels and products. The proposed concept of "engineered carbon reduction" endeavors to broaden the potential renewable carbon feedstock portfolio and to bypass land-use requirements by substituting electricity for solar energy in powering CO_2 reduction, thus "rewiring" the carbon cycle to produce reduced forms of carbon without photosynthesis (Figure 2).

Reducing the Oxidation State of Carbon

CO_2 is the most oxidized form of carbon, and it is an extremely stable, low-energy molecule. Conceptually, the oxidation state of an atom within a molecule is the relative charge an atom would experience. Table 1 shows the structure and oxidation state of carbon for CO_2 and some reduced molecules. The carbon atom in a molecule of CO_2 has an oxidation state of +4; by adding electrons, the oxidation state of the carbon atom within the CO_2 molecule is "reduced," and new molecules can be formed. In biology, this reduction process is called "fixation," and, in photosynthetic systems, it is performed by the enzyme RuBisCo. Once carbon is reduced, it can be consumed by heterotrophic organisms as a source of carbon or be used to produce energy.

Table 1. Molecules That Can Be Produced from Reducing CO_2

Molecule	Chemical structure	Oxidation state of carbon
Carbon dioxide (CO_2)		+4
Carbon monoxide (CO)		+2
Formic acid (HCO_2H)		+2
Methanol (CH_3OH)		-2
Methane (CH_4)		-4

As stated above, the definitive feature of engineered carbon reduction is reducing the oxidation state of the carbon atom in CO_2 without using photosynthesis. Rewiring carbon reduction in such a manner requires a large amount of external energy input in the form of electricity. Due to recent trends in the power sector, each electron on the electricity grid in the United States is becoming cheaper and cleaner. These trends, along with deployments of carbon capture, present an opportunity to engineer and establish new pathways for renewable carbon-based fuels and products that avoid land-use requirements and increase the availability of renewable carbon and the overall carbon efficiency of the economy.

Engineering Tools To Enable Carbon-Negative Pathways and Large-Scale Carbon Management

The Engineered Carbon Reduction Listening Day sought to identify technologies and strategies to enable CO_2 reduction and utilization without photosynthesis. Engineering systems to industrialize carbon reduction without inefficient photosynthesis or fertile land requirements creates new and auspicious opportunities for large-scale carbon management. In fact, one can envision or create numerous unique carbon-neutral or carbon-negative pathways using captured atmospheric or waste CO_2 as feedstock to produce organic chemicals, fuels, materials, products, or combinations of these; this would equip the economy to become a carbon management tool itself.

Carbon-negative pathways could be scaled to increase overall atmospheric carbon removal, and considerations of system scale could be targeted to achieve identified carbon mitigation goals. The particular pathway and product combinations and the product end uses and lifespan would contribute to the pathway's normalized mitigation potential, and life-cycle assessments that characterize the extent and duration of a pathway's carbon storage would be used to quantify its particular value as a carbon management strategy.

However, new thinking and model development will be required to fully account for the carbon benefits and indirect impacts of scaling renewable carbon pathways that avoid intermediate biomass accumulation and fertile land use. So, beyond developing the technologies to effectively bypass land-use requirements for carbon cycling, new analytical frameworks, economic models, and life-cycle methods need to be developed to help direct the best use and deployment of these technologies. Ultimately, the technologies developed in this space can and will be used to transform the carbon-based economy into a new carbon economy that, itself, serves as a mechanism for carbon management.

Carbon Capture and Sequestration

CCS refers to control measures put in place to capture CO_2 produced from industrial or power-generating sources, with the goal to keep the waste carbon from being released into the atmosphere. The technology involves capturing and compressing CO_2 and then either using it for an industrial purpose or injecting it deep into a carefully selected rock formation where it is permanently and safely stored. Together, point-source CO_2 emissions from the power sector (29%) and industrial sector (21%) represented a full 50% of the United States' total carbon footprint in 2015,[3] meaning CCS could drastically reduce greenhouse gas (GHG) emissions domestically and abroad if deployed. Moreover, these CO_2 waste streams represent a sizeable feedstock supply for valorization.

Today in the United States, there are several large-scale facilities in operation that capture at least 0.5 million tons per year of CO_2. Most of these large-scale CCS operations perform enhanced oil recovery, utilizing the waste gas to increase the output of oil wells that have dropped in production volumes. By injecting CO_2 into such oil reservoirs, the viscosity of the oil drops, and it can be pumped from the reservoir while a portion of the CO_2 stays trapped underground. Notably, one large-scale commercial facility in the country, an ethanol biorefinery in Decatur, Illinois, captures CO_2 with the sole purpose of underground storage.

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[3] U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, 1990–2015 (Washington, DC: EPA, April 2017), https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Although a few large-scale facilities exist and operate effectively, one of the major barriers to further CCS deployment is the high energy demand for removal and concentration of the CO_2 from the flue gas. After standard environmental controls, coal flue gas is roughly 10%–15% CO_2, with the remainder of the gas being mostly N_2 and water.[4] In standard monoethanolamine capture systems, flue gas is scrubbed through an amine solution that binds the CO_2. The CO_2-rich stream must then be heated to remove the concentrated CO_2, which is then compressed and piped to either its sequestration or enhanced oil recovery destination. This heating/cooling of the amine scrubber solution, along with compression and capital costs, adds a stiff energy penalty to coal-fired plants, which can require around one-quarter of the produced energy and add about $0.03/kilowatt-hour to the price of electricity.[5] Thus, the economic case for CCS is often considered the main hurdle to adoption at existing facilities. Currently, CCS entities can benefit from a tax credit under 26 U.S. Code § 45Q, which provides $10/ton CO_2 used for enhanced oil recovery or $20/ton for sequestration. However, at estimated costs of capture above $50/ton CO_2,[6] there is still a strong disincentive to install such technology unless more value can be derived from the waste CO_2.

4 "How Is CO_2 Captured?" National Energy Technology Laboratory, https://www.netl.doe.gov/research/coal/carbon-storage/carbon-storage-faqs/co2-capture-process.

5 Jeremy David and Howard Herzog, "The Cost of Carbon Capture," in *Proceedings of 5th International Conference on Greenhouse Gas Control Technologies*, edited by D. J. Williams, R. A. Durie, P. McMullan, C. A. J. Paulson, and A. Y. Smith (Cairns, Australia, 2001), 985–990, https://sequestration.mit.edu/pdf/David_and_Herzog.pdf.

6 Edward S. Rubin, John E. Davison, and Howard J. Herzog, "The Cost of CO_2 Capture and Storage," *International Journal of Greenhouse Gas Control* 40 (2015): 378–400, http://dx.doi.org/10.1016/j.ijggc.2015.05.018.

Carbon Capture and Utilization to Enable Carbon Capture and Storage

The volume of point-source carbon emissions from traditional fossil fueled power plants (coal- and natural gas–fired plants) are too large to reasonably permit carbon management strategies that would capture and use all of their available carbon emissions. In fact, complete utilization would create a two-pronged economic challenge by (1) requiring huge capital and operating costs to establish and maintain such large-scale utilization systems and (2) generating excessive product supplies that would depress product values and prevent overall system viability.

As illustrated in Figure 3, creating valuable products from fossil carbon emissions could offset the cost of CCU and present new opportunities for carbon management at point sources.

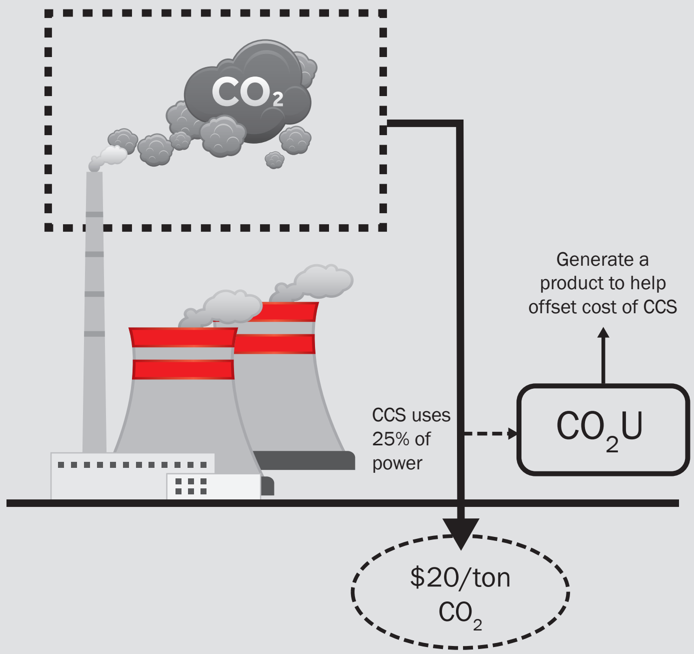

Figure 3. CCU to enable CCS

Systems seeking to manage fossil CO_2 emissions from point sources must consider how to adapt the system design to the size of the waste stream and optimize the product generation to match real-time price and demand targets to achieve overall viability. Establishing the necessary economic conditions to allow for CCS by creating value from a small fractional stream of the CO_2 emitted is one way that new CCU technologies could enable CCS.

Although there are numerous variables to consider—including product selection, market size, price, and the fraction of the waste carbon stream to be directed for use relative to storage—there may be unique opportunities to incentivize CCS through CCU. Identifying products at appropriate volumes and prices that could be generated from power plants' waste CO_2, could offset the cost of CCS for the remaining carbon in the emissions stream and could offer new carbon management strategies for fossil fuels.

Workshop Overview

On July 8, 2017, BETO held the Engineered Carbon Reduction Listening Day to gather stakeholder input on BETO's Rewiring Carbon Utilization Initiative. This meeting was hosted in conjunction with the second International Solar Fuels Conference, which was organized by the University of California, San Diego's Deep Decarbonization Institute. This biennial conference gathers scientists from around the world working with biological and chemical approaches to utilize solar energy for direct fuel production.

BETO partnered with International Solar Fuels Conference organizers to develop an agenda, which provided event attendees with overviews of the state of technology of novel engineered carbon reduction strategies and then solicited expert input on the challenges, opportunities, and resources needed to support advances in the field. The listening day began with presentations from public- and private-sector speakers covering topics related to methanogenic, chemolithotrophic, photolithotrophic, electrochemical, photoelectrochemical, and thermochemical synthesis of renewable fuels and products from CO_2.[7]

Following the series of presentations, BETO facilitated round table discussions with 47 participants who have expertise in the fields of carbon utilization, biochemistry, catalysis, engineering, and sustainability. The attendees represented nonprofit, academic, government, industry, and national laboratory organizations. The individuals were assigned to one of three groups:

- Group 1: Non-Photosynthetic Biological Carbon Utilization Technologies
- Group 2: Non-Biological Carbon Utilization Technologies
- Group 3: Carbon Management/Sustainability.

Each of the three groups was led by a facilitator and supported by a BETO subject matter expert who asked participants to answer questions related to carbon reduction and upgrading technologies. After each 30-minute discussion, a preselected rapporteur shared highlights and findings with the other groups. Scribes recorded discussions in each group to prepare this listening day summary report. The stakeholder input which follows is a non-attributed aggregation of the comments provided by all three groups of participants.

Listening day attendees provided BETO with valuable input regarding topics related to engineered carbon reduction.

For each of the topics covered, stakeholders provided their perspectives about challenges, opportunities, and resources needed to address gaps in current R&D efforts.

CO_2 Capture and Quality

The topic of CO_2 capture and quality was thought to be beyond the scope of the Engineered Carbon Reduction Listening Day, and discussion of this topic was not initially planned. However, participants considered it critical for the vision of engineered carbon reduction. CO_2 may be captured from combustion sources (power plants operated from combustion of coal, natural gas, oil, or biomass), biochemical conversion processes (e.g., ethanol plants or anaerobic digestors), other industrial processes, or direct air capture. The quality of the CO_2 differs greatly among these sources. Factors that affect CO_2 quality include impurities, volumetric availability, minimum selling price, and production cost, among others. As discussed in the following two sections, CO_2 capture technology and CO_2 sources and cleanup are critical considerations related to CO_2 capture and quality.

[7] Speaker bios and presentation titles are available in Appendix C with links to online presentation files.

CO_2 Capture Technology

There is a general hypothesis that developers of CO_2-reduction technologies could avoid excessive cleanup by focusing on biochemical conversion processes and direct air capture rather than combustion sources (e.g., flue gases) and other industrial processes. Participants noted a need for cheap, efficient carbon capture materials. One area for R&D is remediation of low-concentration CO_2 in high-volume flue gases from power plants; another is direct air capture of CO_2. A lot of work is still needed in this area, but carbon capture itself is largely beyond the scope of BETO's mission. However, participants were very eager to discuss the challenges of CO_2 capture. BETO notes that DOE's Office of Fossil Energy operates a Carbon Storage program[8] that pursues innovation in CCS. Additionally, BETO is involved in other related carbon capture activities (such as algae utilization), but the Office considered such activities beyond the time limitation and scope of this listening day.[9]

CO_2 Sources and Clean-up

Attendees noted that there would be a cost for removing contaminants from CO_2 streams. CO_2 separation and purification technologies are available, but there is a cost for efficiency. Additionally, there is the cost of concentrating CO_2. The source of CO_2 will affect cleanup requirements and associated costs. Cleaner sources, as participants commented, could include biochemical processes (e.g., ethanol plants and anaerobic digesters) or direct air capture; these could be more viable for reduction technologies, whereas CCS would be a better play for combustion sources of CO_2. In general, attendees accepted that CO_2 source affects cost and variability and noted that, given the likelihood of substantially diminished CO_2 availability from traditional fossil power generation due to future closures, R&D expenditures should not be diverted towards optimizing capture and cleanup for such streams.

Non-Photosynthetic Biological Carbon Reduction

Engineered CO_2 reduction revolves around reducing CO_2 without using photosynthesis. The listening day plenary presentations described several sub-types of biological techniques to attendees. This section introduces the techniques presented during the morning plenaries:

- Mich Hein of Electrochaea presented[10] on Electrochaea's power-to-gas technology, which relies on methanogenesis. Hydrogenotrophic methanogens can survive on CO_2 as their carbon source and convert the carbon to methane using hydrogen as their reducing equivalent.
- Jeffrey Gralnick of the University of Minnesota presented[11] on microbial electrosynthesis, which relies on chemolithoautotrophy. Chemolithoautotrophs are microorganisms often leveraged in microbial electrosynthesis, which are processes that utilize electricity as an energy source to provide the required reducing equivalents from inorganic sources.
- Harold May of the Medical University of South Carolina also presented on microbial electrosynthesis.
- Dan Nocera of Harvard University presented on chemolithoautotrophy, specifically, bacterial microorganisms that can reduce CO_2 using renewable electricity.[12] The report authors note that there are also other conversion processes possible, such as photoautolithotrophy.

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[8] "Carbon Storage Research," U.S. Department of Energy, Office of Fossil Energy, https://energy.gov/fe/science-innovation/carbon-capture-and-storage-research.

[9] The report authors note that BETO also hosted an Algae Cultivation for Carbon Capture and Utilization Workshop in 2017: https://www.energy.gov/eere/bioenergy/events/algae-cultivation-carbon-capture-and-utilization-workshop. Those interested in carbon capture for photosynthetic carbon utilization are also encouraged to review that workshop report: https://energy.gov/sites/prod/files/2017/09/f37/algae_cultivation_for_carbon_capture_and_utilization_workshop.pdf.

[10] Mich Hein, "Charging the Gas Grid with Solar and Wind Energy—From the 'Fat Duck' to Green Gas" (presentation at the Bioenergy Technologies Office's Engineered Carbon Reduction Listening Day, La Jolla, CA, July 8, 2017), https://energy.gov/sites/prod/files/2017/08/f36/hein_ECRLD.pdf.

[11] Jeffrey Gralnick, "Driving Microbial Metabolism with Electricity: Challenges and Opportunities in Electrosynthesis" (presentation at the Bioenergy Technologies Office's Engineered Carbon Reduction Listening Day, La Jolla, CA, July 8, 2017), https://energy.gov/sites/prod/files/2017/08/f36/gralnick_ecrld.pdf.

[12] Chong Liu, Kelsey K. Sakimoto, Brendan C. Colón, Pamela A. Silver, and Daniel G. Nocera, "Ambient Nitrogen Reduction Cycle Using a Hybrid Inorganic–Biological System," *Proceedings of the National Academy of Sciences* 114, no. 25 (2017): 6450–6455, http://www.pnas.org/content/114/25/6450.full.pdf.

Stakeholders identified several non-photosynthetic biological carbon reduction challenges, including the following:

- Redox balancing
- Pathway engineering
- Multi-phase mass transport and surface area limitations
- Water oxidation
- Durability
- Scale-up from lab to pilot to commercial
- Interfacing with thermocatalytic processes.

Attendees described opportunities for non-photosynthetic biological carbon reduction connected with the electrical grid sector, the biotechnology sector, and the petroleum sector. These opportunities include the following:

- Power-to-gas technology
- Process integration and refinery integration
- Mid-term to long-term developments.

Attendees also discussed a number of needs for non-photosynthetic biological carbon reduction, including the following:

- Broaden the scope of R&D funding
- Planning R&D funding
- Engaging stakeholders.

Non-Photosynthetic Biological Carbon Reduction Challenges

Redox Balancing

Attendees made several comments on the challenge of properly balancing reduction and oxidation reactions in cellular metabolism (commonly called redox balancing). Reduced nicotinamide adenine dinucleotide phosphate (NADPH) supplies electrons as the driving force for most synthesis reactions in biological systems. The rate of reducing power and product synthesis is limited by the regeneration of NADPH. Relying on the tricarboxylic acid cycle for reducing equivalents may not be sufficient to reduce CO_2 from a source or achieve industrially-relevant product titers.

As an alternative, Advanced Research Projects Agency – Energy's ELECTROFUELS program[13] focused on chemolithotrophs to convert CO_2 to fuels. In these systems, electricity is used to generate inorganic reducing equivalents, which provide the energy needed to reduce CO_2. These processes require both the extracellular generation of reducing equivalents, such as hydrogen, and the transfer of such equivalents across the cell membrane.

The transfer of hydrogen across the membrane is reasonably well-understood. However, electrofuels processes that rely on the direct transfer of electrons across the membrane to power CO_2 reduction are less established, and the prospects—even long-term—for scaling such systems are widely debated.

In either case, non-photosynthetic autotrophic systems, whether powered with inorganic intermediates or directly with electrons, can theoretically achieve greater energy and carbon efficiencies than photosynthetic systems and, thus, are worth continued exploration.

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[13] "Electrofuels," Advanced Research Projects Agency – Energy, April 29, 2010, https://arpa-e.energy.gov/?q=arpa-e-programs/electrofuels.

Pathway Engineering

Despite the rapid and extensive advances in pathway engineering and synthetic biology that have been made in recent years, these tools have yet to be extensively leveraged to engineer non-photosynthetic biological CO_2 reduction pathways. Metabolic pathway development can be slow, especially for biochemical CO_2 reduction. Thus, several attendees noted the unique challenges of pathway engineering and metabolomics. Specifically, attendees identified the challenge of designing the shortest electron paths and exploiting these to avoid byproduct formation and side reactions. Suicide metabolites and toxic product generation inhibit steady-state growth in bioreactor systems; proactive pathway design, learning, and testing are needed to address the challenge of pathway engineering for non-photosynthetic biochemical reduction systems.

Multi-Phase Mass Transport and Surface Area Limitations

Powering CO2 reduction non-photosynthetically via biological systems requires delivering either inorganic reducing equivalents or electrons to the cell. Attendees noted the challenges of both multi-phase mass transfer and surface area exposure to electron sources in bioreactor systems.

Attendees noted a hydrogen mass transfer rate limitation, as mass transfer of gases into aqueous media can be difficult and rate limiting for many processes. Other mass transfer limitations were noted as well, including reactant input and product isolation limitations. Indeed, separation processes for biomass and other products are relatively energy-intensive and difficult. These challenges are not unique to non-photosynthetic biochemical CO_2 reduction systems, and BETO already has ongoing efforts to address mass-transfer and separations challenges. For example, the Bioprocessing Separations Consortium aims to develop cost-effective, high-performing separations technologies faster through coordinated separations research that targets challenges relevant to industry.[14]

A unique challenge in this area is delivering electrons to the cell for direct electron-powered CO_2 reduction. However, participants did not highlight these systems as a major near-term opportunity.

Water Oxidation

Water oxidation refers to one of the half reactions of water splitting. In water oxidation, one molecule of water yields one molecule of dioxygen (O_2) with four protons and four electrons. Better catalysts for water oxidation are still needed. The oxidation step of water splitting naturally occurs in Photosystem II in plants, but this is challenging to duplicate non-photosynthetically. The report authors note that DOE-EERE's Fuel Cell Technologies Office has a Hydrogen Production program[15] that investigates water splitting in non-photosynthetic biological processes, including a 2013 workshop and subsequent report.[16]

Durability

Attendees noted that durability of microorganisms is a major challenge. Key parameters that cause microorganism crashes include oxygen sensitivity and death or inactivation by other causes, such as product inhibition or contamination. More work is needed to identify and engineer new and more robust chassis for performing biological non-photosynthetic CO_2 reduction.

Scale-Up from Lab to Pilot to Commercial

Several attendees commented on the scale-up challenges surrounding unit process integration and increasing throughput. Specific notes suggested that unit processes and electrode activity do not scale up efficiently from lab to industrial scales easily while maintaining realistic and industrially relevant operating conditions.

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[14] Bioprocessing Separations Consortium, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, https://www.bioesep.org/.

[15] "Hydrogen Production," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, https://energy.gov/eere/fuelcells/hydrogen-production.

[16] K. Randolph and S. Studer, *2013 Biological Hydrogen Production Workshop Final Report* (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, November 2013), https://energy.gov/sites/prod/files/2014/03/f12/bio_h2_workshop_final_report.pdf.

Although participants in the biological technologies group predicted great uncertainty, both technical and financial, for commercial bioreactor systems intending to use variable stranded electricity resources (excess renewable electrons), the dynamic nature of electricity availability was beyond the scope of this group's consideration. Indeed, attendees stressed that additional resources are needed to fund basic scientific discovery before decisions about system operation and electron availability can be considered.

The group highlighted a need for communicating and understanding the long-term availability of affordable electricity; this was a topic of greater discussion in other groups and will be addressed later in this report.

Integrating with Thermocatalytic Processes

Attendees were excited about the potential for integrating and combining biological systems with non-biological (thermocatalytic, electrocatalytic, photocatalytic) systems to realize unique benefits from each catalytic approach. Thus, the participants from biological backgrounds were curious to learn more about catalytic efficiencies and selectivity. The integration of biological and non-biological components is still challenging. There is a need for fundamental research on the interface between microorganisms and the non-biological systems, but participants were clear about their interest in studying new carbon conversion systems that might integrate multiple catalytic approaches. For example, systems employing a non-biological approach to reducing CO_2 to generate an amenable reduced intermediate for biological upgrading could be designed and may improve the system's overall efficiency by decoupling carbon reduction and carbon upgrading. Such an approach would avoid the difficulties in the slow rates associated with biological CO_2 reduction while harnessing the unique capabilities of biology in carbon-carbon bond formation.

Non-Photosynthetic Biological Carbon Reduction Opportunities

Power-to-Gas Technologies

Participants were excited about the potential for power-to-gas technologies. They felt this was an opportunity for the engineered carbon reduction community to leverage the unique successes and challenges of the evolving electrical grid sector. Specifically, such technologies may incorporate hydrogenotrophic methanogenic microorganisms that have the capability for biological methanation[17] of CO_2 to methane, with hydrogen via water electrolysis powered by smart grid management. While participants saw power-to-gas as a near-term win, they noted that the economic success of technologies that generate synthetic natural gas depends heavily on natural gas prices, which are extremely low in the United States. Power-to-gas can serve as a method of energy storage and address challenges associated with curtailed renewable electricity.

Mich Hein from Electrochaea's morning plenary presentation provided an overview of a process that utilizes a strain of methanogenic archaea that can reduce CO_2 to methane. This microorganism requires electrons from hydrogen to power the reduction of CO_2. Electrochaea's strategy is to exploit intermittent inexpensive energy from the grid as the source for electrolysis of water to produce the needed hydrogen. See Figure 4 for an illustration of this power-to-gas system design.

[17] Conversion of carbon dioxide or carbon monoxide to methane through hydrogenation.

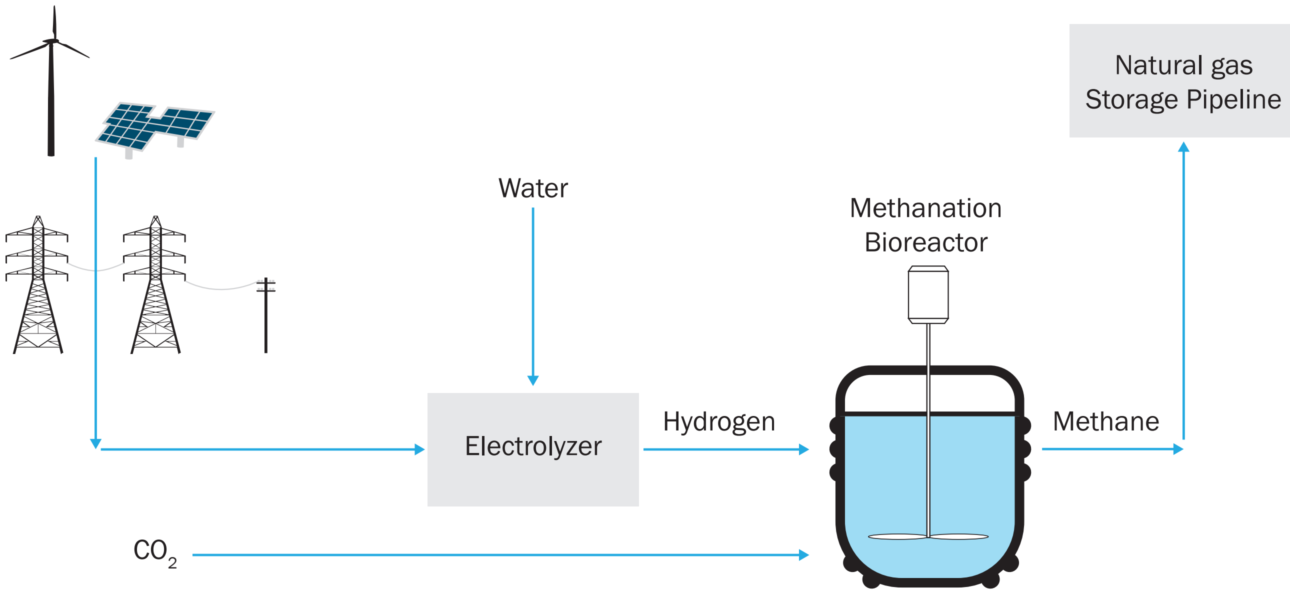

Figure 4. Sample biological power-to-gas system design. Such power-to-gas technologies rely on microorganisms that can take hydrogen (generated from splitting water) and CO_2 and convert them into methane, which can then enter the existing pipeline structure across the country. If operated at times of plentiful renewable electricity, this can act as a form of grid-scale energy storage.

Process Integration and Refinery Integration

Attendees stated potential for integrating non-photosynthetic biological reduction at petroleum refineries. Electromethanogenesis, such as power-to-gas, is relatively simple and compatible with existing infrastructure. One stated example of refinery integration would be electromethanogenic bioreactors coupled to steam methane reformers for producing carbon monoxide, which would be compatible as upstream feedstock producers to syngas utilization operations.

Mid-Term to Long-Term Developments

Attendees suggested the short-term opportunity for non-photosynthetic biological carbon reduction could be methane production, but as noted, this may require additional upgrading due to low natural gas prices. Attendees suggested thermocatalytic conversion of the methane to carbon monoxide. Simultaneously, there could be mid- and long-term opportunities for direct biological conversion from CO_2 to carbon monoxide. Carbon monoxide generation via microbial pathways is not trivial, especially because the product is toxic to microorganisms. Microbial carbon monoxide generation is a mid-term development at least, requiring more than 5 years of development.

Non-Photosynthetic Biological Carbon Reduction Needs

Broaden the Scope of R&D Funding

Participants noted the need for a better understanding of the interfaces within systems that combine different biological and non-biological approaches to reduce CO_2. This refers not only to reactor interfaces but also to those knowledge interfaces between different areas of expertise. Shared learning from cross-field cooperation would improve understanding of fundamental mechanisms of catalysis. Participants were eager for a loosening of specific funding requirements that limit the scope of development. More joint funding announcements could be an opportunity to satisfy this constraint. Additionally, communication between fundamental science and applied R&D is needed. Participants expressed interest in funding opportunities with less prescriptive milestones and timelines. Participants also raised attention to the "valley of death" and the transition between DOE funding agencies and other funding partners. Participants were excited about the concept of a "moon-shot effort" for a fully integrated, large-scale process that non-photosynthetically reduces CO_2 and converts it to fuels and products.

Stakeholder Engagement

Participants requested several methods of stakeholder engagement. One method was to help establish partnerships and networks that will lead to offtake agreements. BETO methods to accomplish this could include additional workshops and listening days, and the Office could also publish responses from a relevant request for information. Attendees also request that BETO address standardization and metrics. In other projects, BETO addresses standardization through funding the national laboratories to build laboratory analytical procedures and assisting in programs such as ASTM International standards development and International Energy Agency Bioenergy tasks. DOE has also supported the development of metrics, such as in solar photovoltaics.

Engineering the "Artificial Leaf": Technologies to Industrialize CO_2 Reduction and Utilization

Daniel Nocera, one of the workshop's expert speakers, helped engineer a non-photosynthetic system to produce liquid fuels from sunlight, CO_2, and water. In fact, the efficiencies reported for this "artificial photosynthetic" route are more than 10 times that of photosynthesis. The specific system couples a water splitting catalytic process and a hydrogen-oxidizing biosynthetic pathway that achieves nearly a 10% CO_2 reduction energy efficiency.

Hybrid approaches such as this can be engineered to leverage inherent advantages of catalytic and biological conversion processes simultaneously, and workshop attendees identified such approaches as a particular opportunity for directed R&D.

Beyond the specific reduction energy efficiency improvements, engineered carbon reduction systems could offer substantial life-cycle and carbon-management benefits by offering the ability to bypass land-use requirements carbon cycling and avoiding inefficiencies from deconstructing and then upgrading traditional biomass feedstocks.

Figure 5. The "artificial leaf" has been engineered to mimic the carbon utilizing functions of plants, but with far greater efficiencies than photosynthesis.

Non-Biological Carbon Reduction

The Engineered Carbon Reduction Listening Day plenary presentations highlighted three catalytic technologies within the general category of non-biological carbon reduction. Kendra Kuhl of Opus 12 presented on electrocatalytic CO_2 reduction.[18] Harry Atwater of the Joint Center for Artificial Photosynthesis presented on photoelectrochemical reduction of CO_2.[19] Bill Tumas of the National Renewable Energy Laboratory also discussed photoelectrochemical conversion, from the perspective of water splitting.[20] Such photoelectrochemical catalysis approaches use semiconductor-type catalytic materials and light harvesting systems where the catalyst converts light to free electrons as the source of the reducing power. Finally, Anthony Martino of Sandia National Laboratories presented on solar-thermochemical reduction of CO_2.[21] Solar-driven thermochemical catalysis involves utilizing concentrated solar power as a heat source for thermally reducing metal oxides, which are then used for reducing CO_2 to syngas.

Attendees identified the challenges facing non-biological carbon reduction technologies during the afternoon breakout session:

- The interface between CO_2 feedstocks and conversion technologies
- Catalyst durability
- Electrolytic cell overpotential
- Reactor stability
- Process integration and process intensification.

Attendees also discussed several opportunities for non-biological carbon reduction, including the following:

- Advanced catalyst characterization
- Design for catalysts with high yield and selectivity
- Experimental verifications at industrially relevant conditions
- Process intensification
- Chemical industry integration
- Bioenergy refinery integration
- Photoabsorbers for photocatalysis
- Refinery integration
- R&D programs
- New materials for improving electrolytic cell overpotential.

Finally, attendees discussed R&D needs related to non-biological carbon reduction, including the following:

- Benchmarking and roadmapping
- Machine learning
- Biological–thermocatalytic–electrochemical interface
- Thermochemical deconstruction via concentrated solar power.

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[18] Kendra Kuhl, “Recycling Carbon Dioxide through PEM Electrolysis” (presentation at the Bioenergy Technologies Office’s Engineered Carbon Reduction Listening Day, La Jolla, CA, July 8, 2017), https://energy.gov/sites/prod/files/2017/08/f36/kuhl_ecrld.pdf.

[19] Harry Atwater, “Artificial Photosynthesis—The Selective CO_2 Reduction Challenge” (presentation at the Bioenergy Technologies Office’s Engineered Carbon Reduction Listening Day, La Jolla, CA, July 8, 2017), https://energy.gov/sites/prod/files/2017/08/f36/atwater_ECRLD.pdf.

[20] Bill Tumas, “Research Challenges for Non-Photosynthetic Solar Fuels Production” (presentation at the Bioenergy Technologies Office’s Engineered Carbon Reduction Listening Day, La Jolla, CA, July 8, 2017), https://energy.gov/sites/prod/files/2017/08/f36/tumas_ecrld.pdf.

[21] Anthony Martino, “Sunshine to Petrol: Reimagining Transportation Fuels” (presentation at the Bioenergy Technologies Office’s Engineered Carbon Reduction Listening Day, La Jolla, CA, July 8, 2017), https://energy.gov/sites/prod/files/2017/08/f36/martino_ecrld.pdf.

Non-Biological Carbon Reduction Challenges

Feedstock-Conversion Interface

Several participants brought up the interface between CO_2 feedstocks and the technology used to reduce them. For one, participants commented on the challenge of working with non- or minimally- purified feedstocks. To avoid purification needs, participants suggested using CO_2 from air—instead of from flue gas or other sources. However, some pointed out that direct air capture technology is in its infancy and that there are other nearer-term technologies capable to aid a vision of decarbonization. Attendees also pointed out that certain high-concentration CO_2 waste streams from existing biochemical conversion processes, like ethanol fermentation, could be an appealing feedstock for carbon reduction catalysts. BETO has learned from its experience in bioenergy conversion with a wide array of feedstocks that interfacing between feedstocks and conversion technologies is a significant challenge. This interface requires different experts, from CO_2 sources and from CO_2 conversion engineers, to come together and discuss overlapping challenges.

One consideration drawn from the discussion is that CO_2 from direct air capture or from biochemical conversion processes may be cleaner than CO_2 from power plants. A possible strategy is to engage the biochemical conversion technology providers as first adopters. Sampling and information on the purity and concentration of CO_2 from CCS at power generating units would be of interest.

Electrolytic Cell Overpotential

Most of the non-biological carbon reduction challenges discussed apply to all relevant technologies, though there were specific considerations raised that relate to electrocatalytic and photoelectrochemical reduction technologies.

Catalytic CO_2 reduction is a multi-step process of CO_2 adsorbing onto a catalyst site, exchanging electrons, and desorbing. The process involves more electrons than hydrogen evolution or oxygen reduction. Overpotential is the term for measuring the wasted energy due to the multi-step kinetics. Since multiple electrons must be transferred each with its own theoretical energy requirement, the overpotential value describes the energy efficiency of the overall process. Attendees strongly stressed the need for reducing overpotential for CO_2 reduction.[22]

Harry Atwater, from the California Institute of Technology's Joint Center for Artificial Photosynthesis, presented on work by colleagues in reducing CO_2 to formate. The photoelectrochemical design utilizes a photoanode in a highly basic solution. Hydroxide ions are oxidized, and electrons are released. A bipolar membrane separates the photoanode in the basic solution from a dark cathode (nanoparticles of palladium on carbon, in the case presented) in a solution (bicarbonate, in the case presented). The cathode utilizes the electrons to reduce CO_2 to formate. Characteristic results reported in such processes include the overpotential and the Faradaic efficiency. The overpotential characterizes the cell's experimental voltage efficiency. The Faradaic efficiency characterizes the electron transfer efficiency at a given current density.

Design for Durable Catalysts

Broadly speaking, catalyst development includes four general steps: catalyst design, synthesis, characterization, and evaluation of performance. Methodologies such as high-throughput screening enable fast evaluation of performance. However, smart catalyst design requires a strong fundamental understanding of the process that will use the catalyst. Engineered carbon reduction is still nascent, so design principles are not widely accepted or available. Catalyst developers in CO_2 reduction are likely deriving their experience from the wealth of knowledge in petroleum and petrochemical catalysis or emissions catalysis. This forces investigators exploring CO_2 catalytic reduction to start from materials developed and optimized for other processes.

[22] The report authors suggest this review paper for further discussion: Zhi Wei She, Jakob Kibsgaard, Colin F. Dickens, Ib Chorkendorff, Jens K. Nørskov, and Thomas F. Jaramillo, "Combining Theory and Experiment in Electrocatalysis: Insights into Materials Design," *Science* 335, no. 6321 (2017), http://science.sciencemag.org/content/355/6321/eaad4998.

Thus, attendees noted the lack of design principles or universal techniques for rationally improving catalysts for CO_2 reduction applications, with the field instead being discovery-driven. In general, the design process should be driven to create catalysts that are cheap, efficient, and robust and that produce a long-lived reduction device with good efficiency. Attendees referred to some CO_2 capture techniques that could temporarily hold CO_2 as bicarbonate in aqueous solutions that would likely contain other contaminants from the carbon waste gas stream. If catalysts were developed that could operate in such "dirty" systems, this would allow better integration with approaches that use electrolyzers for hydrogen production. Additionally, there are considerations surrounding earth-abundant and inexpensive materials. Attendees noted that no current catalyst meets all needs.

Reactor Stability

There are interrelated chemical factors affecting reactor stability, where chemical composition and mass transport would have feedback effect. Attendees noted CO_2 concentration in solution in particular since the introduction of CO_2 into a reactor will lower the pH of the solution, impacting the solubility of CO_2 and possibly other materials in the reactor.

Process Integration and Process Intensification

To confirm the value of catalyst and reactor design, there is a need for an initial commercial success, but attendees said presently there is a lack of funding for pilot to scale. Additionally, there are challenges for scalability of electrochemical, photochemical, and other catalytic methods. Participants desired systems and reactors that are designed for a distributed-scale infrastructure, and the integration of individual technologies is essential to configure processes that can be commercialized; this relies on integrating catalyst and reactor, reactor and process, and process and market. The report authors note that BETO's general experience in catalysis indicates that that catalysts are first evaluated at small-scale in high-throughput equipment and lab-scale stirred tank reactors, flow reactors, and other readily available equipment that can be purchased or built onsite. The envisioned reactor at commercial scale may not resemble the laboratory equipment.

Non-Biological Carbon Reduction Opportunities

Advanced Catalyst Characterization

Heterogeneous catalysis is a very active field for energy research. A review of current catalysts that reduce carbon would support the field.[23] Attendees said there is an opportunity now to systematically study heterogeneous catalysts (with composition and morphology control). Key activities include exploring new materials for thermochemical and photoelectrochemical catalysis. Attendees also mentioned that the field of solar thermochemical CO_2 reduction needs more work in redox/catalyst materials.

BETO has worked with DOE national laboratories to oversee the Chemical Catalysis for Bioenergy Consortium, which consists of catalysis experts that leverage their capabilities for synthesis, characterization, and evaluation of catalysts for biomass conversion. The Chemical Catalysis for Bioenergy Consortium is one of seven consortia within the Energy Materials Network (EMN), which crosscuts EERE. The EMN is a DOE contribution to the Materials Genome Initiative. EERE's Fuel Cell Technologies Office manages another EMN consortium, HydroGEN, which consists of six DOE laboratories and addresses challenges in advanced water splitting materials by leveraging capabilities in photoelectrochemical, solar thermochemical, and low- and high-temperature electrolytic water splitting. Following the framework of the Materials Genome Initiative, the EMN consortia work together on common themes surrounding data management of characterizing materials and could be an asset in any catalyst effort.

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[23] A recent review paper is suggested for further information: Zhi Wei She, Jakob Kibsgaard, Colin F. Dickens, Ib Chorkendorff, Jens K. Nørskov, and Thomas F. Jaramillo, "Combining Theory and Experiment in Electrocatalysis: Insights into Materials Design," *Science* 335, no. 6321 (2017), http://science.sciencemag.org/content/355/6321/eaad4998.

Design for Catalysts with High Yield and Selectivity

There are a number of parameters for characterizing catalyst performance. Attendees said there is a lack of catalysts that are both active and selective, and an effective catalyst must be both. Specifically, there is poor understanding of how reaction conditions affect activity. Participants also noted redox materials as a promising source. In this context, redox materials generally refer to electrocatalysts capable of reducing CO_2 when electrical energy is added. DOE's Office of Science's Basic Energy Sciences program has reported several discoveries in catalytic conversion of CO_2 to intermediates, including formic acid[24] and ethanol.[25] Due to the success of related research, attendees were optimistic when discussing whether this challenge can reasonably be overcome, leading to an increase in catalyst production yields and more selective specifications.

Experimental Verifications at Industrially Relevant Conditions

Issues surrounding catalyst validation at industrially relevant conditions were a frequent discussion topic. Variabilities such as solvents, temperature, local CO_2 concentrations, and pH impact reaction conditions. Accelerated testing, consisting of long-time experimental runs of varying conditions, is needed to estimate lifetime and durability of catalysts and related technologies. The correct scale to test a catalyst cannot be known without known scaling conditions. Participants questioned how catalyst activity may be used to predict scale-up. Attendees familiar with BETO and EERE at large commented that there is too much risk for industry to manage scale-up on its own if government support ends at the point of applied R&D. In general, attendees were eager to state that risk must be evaluated before scale-up and that government should be involved..

Process Intensification

Attendees noted that there is promise for modular reactor engineering for non-biological carbon utilization technologies, which may be deployed at smaller CO_2 emission sources, such as breweries or smaller industrial processes. This would require improved small reactor design. Electrolyzers are built as single cells, and they can fill this role; scale-up is also possible as they can be assembled in cell stacks. During the morning session, Kendra Kuhl of Opus 12 presented on Opus 12's technology for electrochemical reduction of CO_2. Opus 12 uses a specialized polymer electrolyte membrane (PEM) reactor, which splits water to make hydrogen and has a metal catalyst layer inserted within to reduce CO_2 to carbon monoxide. The resulting syngas can be biologically or chemically upgraded to fuels or products. Small, modular technologies such as this would fit the deployable niche at point sources of CO_2 described by attendees.

In both thermocatalytic reactors and bioreactors that convert biomass, the conversion process often involves multiple phases of solids of various particle size, aqueous and organic liquids, and gases; these different phases complicate reactor design, scaling, and operational up-time. Reactors that use gases such as CO_2 as the feedstock avoid some of these feedstock handling issues that have stymied industrial-scale biomass conversion.

Chemical Industry Integration

Participants discussed coupling electrochemical CO_2 reduction technologies to biological upgrading processes. Of specific interest is the possibility to integrate electrochemical CO_2 reduction to C_1 molecules with a biological upgrading route convert reduced carbon intermediates to products of higher carbon number. This type of integration couples the advantages of using electricity to power CO_2 reduction with established biological carbon manipulation strategies. Attendees stated that BETO is well-suited to drive collaboration between these disciplines. These individuals also saw this approach as a "low-hanging" fruit for a near-term success in CO_2 utilization.

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[24] "Capturing and Converting CO_2 in a Single Step," U.S. Department of Energy, Office of Science, last modified January 3, 2016, https://science.energy.gov/bes/highlights/2015/bes-2015-08-h/.

[25] "A Catalystic Shock," U.S. Department of Energy, Office of Science, last modified November 14, 2017, https://science.energy.gov/bes/highlights/2017/bes-2017-05-g/.

Bioenergy Refinery Integration

CO_2 is produced from several different commercial bioenergy processes and is generally treated as a waste. Ethanol plants that convert sugar from corn starch and other sources into ethanol release two moles of CO_2 and two moles of ethanol for every mole of sugar that is converted; this roughly equates to over 1 ton of CO_2 being produced for every ton of ethanol. Thus, the integration of CO_2 reduction technologies may provide benefit at ethanol plants and recover some of that wasted one-third of input carbon.

Anaerobic digestion of organic waste streams to biogas generates roughly a 2:1 mixture of methane and CO_2. This process was seen as another opportunity for increased carbon efficiency via the incorporation of CO_2 reduction technologies. Out of the array of CO_2 reduction technologies that could be integrated at such point sources, attendees suggested electrolyzers functionalized with carbon-carbon bond formation technology as one possible consideration. The report authors note that electrolyzers are generally considered scalable reactors suited for distributed resources.[26] The suggestion refers to siting an electrolyzer at the anaerobic digestor and then directing carbon reduction intermediates onsite to an upgrading reactor for manufacturing fuels and products. An alternative solution mentioned for anaerobic digesters was generating hydrogen and applying it to the digester to increase the methane conversion efficiency of the process.

Refinery Integration

Attendees expressed interest in seeing CO_2 reduction integrated with commercialized refinery processes, such as methanol[27] synthesis from syngas. Use of syngas as a commercial feedstock for Fischer-Tropsch synthesis of hydrocarbons, as well as methanol or ammonia production, is currently at commercial scale.

Photoabsorbers for Photocatalysis

There was discussion around the need for low-cost, efficient photoabsorbers for photoelectrochemical conversion technologies for CO_2 reduction. DOE's Basic Energy Sciences program's Chemical Sciences, Geosciences, and Biosciences Division has a research area focused on solar photochemistry, which includes investigating light absorption.[28] The Solar Energy Technologies Office also has observed long-term, high-potential R&D opportunities in exploring metal oxides and metal sulfides for new photovoltaic absorbers.[29] Additionally, photoabsorption intersects with DOE's Fuel Cell Technologies Office's activities related to photoelectrochemical water splitting.[30]

R&D Programs

Attendees had specific suggestions on R&D programs they would like to see. Programs that encourage interdisciplinary research collaboration would be preferred. Also, there was interest in developing a cost-estimating system for catalyst technology, perhaps using collaboration with companies for validation. Similarly, the lack of established metrics and protocols across the field was seen as a barrier to catalyst development and perhaps a gap BETO can fill.

New Materials for Improving Electrolytic Cell Overpotential

Attendees stated that there are promising developments in transition metal phosphide nanomaterials, and further development of these materials for overpotential reduction would be an opportunity. The report authors note that

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26 "Hydrogen Production: Electrolysis," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, https://energy.gov/eere/fuelcells/hydrogen-production-electrolysis.

27 "Syngas Conversion to Methanol," National Energy Technology Laboratory, https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/methanol.

28 "Research Areas: Solar Photochemistry," U.S. Department of Energy, Office of Science, last modified March 5, 2016, https://science.energy.gov/bes/csgb/research-areas/solar-photochemistry/.

29 SunShot Initiative "Photovoltaics: Technologies, Cost, and Performance," in Sun Shot Vision Study (SunShot Initiative, February 2012), 69–96, https://www.energy.gov/sites/prod/files/2014/01/f7/47927_chapter4.pdf.

30 "DOE Technical Targets for Hydrogen Production from Photoelectrochemical Water Splitting," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, https://energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-photoelectrochemical-water-splitting.

the Fuel Cell Technologies Office's *Annual Merit Review Proceedings* is a good resource for recently funded DOE projects dealing with catalytically splitting water for hydrogen production.[31] The report authors also note that a literature search confirms there is a wealth of recent review papers on transition metal phosphide nanomaterials for water splitting.

Non-Biological Carbon Reduction Needs

Benchmarking and Road-Mapping

Participants noted that the National Renewable Energy Laboratory's efforts in benchmarking photovoltaics performance have been a valuable achievement in the solar energy industry.[32] Such benchmarking could be used to confirm the validity of reported catalyst behavior. A similar effort for non-biological CO_2 reduction technologies would foster innovation, track progress, and communicate impact.

Some attendees mentioned overpotential as one key metric that should be benchmarked, while others suggested catalyst activity, efficiency, and selectivity. The framework for benchmarking would also require a development roadmap, specific technology targets, and standardized measurement protocols and operating procedures. There was a lot of interest in the approach, although it was noted that standardization can deter creativity.

Machine Learning

Computational and validated bioenergetics could expedite the identification of effective pathways. Artificial intelligence and machine learning provides the capacity to narrow down the field of possible solutions once data sets are sufficiently in place. The report authors note that efforts following the framework of the Materials Genome Initiative have led to recent successes in utilizing machine learning to discover new catalytic materials.[33]

Biological–Thermocatalytic–Electrochemical Interface

Participants, especially from thermocatalytic and electrochemical backgrounds, expressed a strong interest in collaborating with biologists on exploring opportunities for non-biological CO_2 reduction coupled with biological upgrading. One suggested approach was to demonstrate CO_2 electrolysis followed by biological upgrading to products.

Thermochemical Reduction via Concentrated Solar Power

Attendees were encouraged by existing efforts related to solar thermochemical CO_2 reduction. During the plenary session, Anthony Martino from Sandia National Laboratories described the "Sunshine to Petrol" program. This program leverages a two-step thermochemical cycle using concentrated solar power to heat and reduce a metal oxide. The hot metal oxide subsequently reduces CO_2 and H_2O to CO and H_2, respectively. Attendees noted that this approach is perhaps overlooked when CO_2 reduction technologies are surveyed.

Non-Photosynthetic Biological Upgrading of Intermediates

Engineered Carbon Reduction Listening Day attendees indicated that they see great potential for biotechnology innovation in upgrading intermediate chemicals such as carbon monoxide, formic acid, or methane into fuels and products. Attendees expect that such innovation would valorize carbon reduction intermediates more easily produced through non-biological technologies. A critical step in achieving this innovation, according to stakeholders, is the need for coordination and collaboration across biological and non-biological areas of carbon utilization expertise.

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[31] "2017 Annual Merit Review Proceedings," U.S. Department of Energy, Hydrogen and Fuel Cells Program, https://www.hydrogen.energy.gov/annual_review17_proceedings.html.

[32] NREL has conducted benchmarking of efficiencies for 27 designs for solar cells produced by many different institutions from 1976 through 2017. See this chart for more information: https://www.nrel.gov/pv/assets/images/efficiency-chart.png.

[33] Paul Raccuglia, Katherine C. Elbert, Philip D. F. Adler, Casey Falk, Malia B. Wenny, Aurelio Mollo, Matthias Zeller, Sorelle A. Friedler, Joshua Schrier, and Alexander J. Norquist, "Machine-Learning-Assisted Materials Discovery Using Failed Experiments," *Nature* 533 (2016): 73–77, http://scholarship.haverford.edu/cgi/viewcontent.cgi?article=1069&context=compsci_facpubs.

Breakout sessions identified major opportunities and R&D needs related to upgrading intermediates generated via CO_2 reduction, as listed below. Attendees felt there was significant opportunity in this area though it was clear there is competition for other end uses of the carbon reduction intermediates. This report summarizes the opportunities in three categories:

- Near-term biobased chemicals
- Biological upgrading of carbon monoxide
- Carbon sequestration.

The workshop attendees also identified two specific needs for further R&D in the areas of metabolomics and bioprospecting.

Non-Photosynthetic Biological Upgrading of Intermediates Opportunities

Near-Term Biobased Chemicals

Attendees understood upgrading intermediates to chemicals as a major opportunity, though there is concern that only certain markets could be reached in the near term. Regarding the timeline for private-sector commercialization, stakeholders believe that the technologies currently being produced in pilot scale may be ready for market in the next 3–5 years.

Participants suggested that in the near term, the R&D focus should include chemicals, including chemical precursors and monomers for polymers. Attendees suggested a focus on isopropanol, ethanol, and acetone, as they have large market volumes. Beyond C_4 molecules, stakeholders are skeptical that there is sufficient market demand to justify R&D investments. The report authors note some misalignment here between the stakeholders and BETO. BETO's mission is to support R&D in liquid transportation fuels, bioproducts, and biopower. Liquid transportation fuel molecules mostly have carbon numbers higher than 4. Generally, BETO's vision includes bioproducts to enable biofuels, either through support of platform chemicals or simultaneous bioproduct and biofuel production.[34] Therefore, the report authors note that there is some misalignment between stakeholders' near-term vision and BETO's mission. Nevertheless, to match existing industry infrastructures, attendees recommended targeting chemicals that can be utilized by CO_2 producers. Participants noted stereoselective products as a key target, and while attendees did not discuss particular stereoselective products of interest, the report authors note that common examples are lactic acid, 2,3-butanediol, and amino acids. Biological processes potentially have an advantage in generating such products due to a greater control on stereoselectivity.

Biological Upgrading of CO

Attendees mentioned the potential for utilizing a hybrid process that combines electrochemical reduction of CO_2 to CO, followed by gas fermentation. Currently some gas fermentation companies are utilizing syngas from industrial flue gases or biomass gasification. There is an opportunity for these companies to lead the way in engineered carbon reduction.

Carbon Sequestration

Attendees remarked that bio-mineralization will permanently sequester carbon, but it is out of scope for BETO projects. DOE's Office of Fossil Energy has funded CCS technologies that exploit bio-mineralization.[35]

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[34] "Bioproducts," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, https://www.energy.gov/eere/bioenergy/bioproducts.

[35] "Department of Energy Announces 15 Projects Aimed at Secure Underground Storage of CO_2," U.S. Department of Energy, Office of Fossil Energy, August 11, 2010, https://www.energy.gov/fe/articles/department-energy-announces-15-projects-aimed-secure.

Non-Photosynthetic Biological Upgrading of Intermediates Needs

Metabolomics

Attendees noted the need for metabolic toolboxes for enzyme engineering to create new reactions and pathways. BETO supports enzyme engineering work, design-build-test-learn facilities, and related technologies for deconstructing cellulose and hemicellulose and upgrading cellulosic sugars, lignin, biogas, and bio-derived syngas in many projects under its Conversion R&D Program[36] and Waste-to-Energy activities.[37] BETO also provides support for improving genetic tools for algae.[38]

Bioprospecting

Attendees said they would like to see more strain prospecting and ecological engineering. There are untapped resources for exploring biodiversity and rethinking chemistry based on potential to biologically upgrade common existing platform biomolecules. The DOE Office of Science's Basic Energy Sciences program supports bioprospecting activities, such as genome mapping and DNA sequencing, at the Joint Genome Institute and related centers.[39]

Non-Biological Upgrading of Intermediates

In addition to non-photosynthetic biological technologies, there are also R&D opportunities for non-biological upgrading of the intermediate chemicals that result from carbon reduction processes. Workshop attendees had a lively discussion on the challenges, opportunities, and needs related to non-biological upgrading of carbon reduction intermediates. Even though this area is similar to the petrochemical knowledge of Fischer-Tropsch fuels, the attendees had much to discuss about this topic as it relates to CO_2 utilization. Additionally, attendees expressed interest in improved communication and collaboration between biological and non-biological researchers. In addition to discussing bioproducts and biofuels, attendees also commented on opportunities for upgrading CO_2 to cement, which is within the portfolio of the Office of Fossil Energy.[40]

Primary challenges related to non-biological intermediate chemical upgrading include the following:

- Catalytic upgrading to liquid fuels and chemicals
- Multi-phase mass and heat transport
- Liquid/liquid separations.

Attendees identified the following opportunities for non-biological upgrading of carbon reduction intermediates:

- Biological–thermocatalytic–electrochemical interface
- Catalytic upgrading to liquid fuels and chemicals
- Shared learning from chemical industry
- R&D funding designs

36 "2017 Project Peer Review—Biochemical Conversion," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, https://www.energy.gov/eere/bioenergy/downloads/2017-project-peer-review-biochemical-conversion.

37 "2017 Project Peer Review—Waste to Energy," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, https://www.energy.gov/eere/bioenergy/downloads/2017-project-peer-review-waste-energy.

38 "Energy Department Announces up to $8.8 Million for Innovations in Algae Technology," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, September 8, 2017, https://www.energy.gov/eere/articles/energy-department-announces-88-million-innovations-algae-technology.

39 "Biofuels Strategic Plan," U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, https://science.energy.gov/~/media/ber/pdf/Biofuels_strategic_plan.pdf.

40 Clean Coal Research Program, Carbon Storage Technology Program Plan (U.S. Department of Energy, Office of Fossil Energy, December 2014), http://www.netl.doe.gov/File%20Library/Research/Coal/carbon-storage/Program-Plan-Carbon-Storage.pdf#page=39.

- Intermediates market analysis
- Standards development
- Stakeholder engagement
- LCA and resource assessment.

Attendees suggested that the following resources are needed to advance non-biological carbon upgrading:

- Catalyst design
- Technology-to-market planning
- R&D funding
- Policy
- Value proposition.

Non-Biological Upgrading of Intermediates Challenges

Catalytic Upgrading to Liquid Fuels and Chemicals

Attendees addressed the need for efficient, active catalysts for liquid hydrocarbon fuel synthesis to convert C_1 molecules to products in the carbon number range of C_5 to C_8. The technologies would need to address the upstream feedstock quantities and qualities. The report authors note that there are current thermocatalytic upgrading technologies for fossil methane to liquid fuels at the scales and technology characteristics needed for natural gas upgrading.[41] The report authors thus stress that while specific conversion processes are well-known, these technologies may not necessarily fit the logistics and input stream constraints if integrated into engineered carbon reduction technologies situated near carbon sources, such as ethanol refineries.

Multi-Phase Mass and Heat Transport

Engineered Carbon Reduction Listening Day participants noted that the conversion of gaseous molecules to liquid fuels is a challenge that is often difficult to scale due to heat transfer management. The key to addressing this technical barrier is understanding multi-phase mass transport. Currently, BETO supports related activities, including investigating an indirect liquefaction conversion pathway where biomass-derived dimethyl ether is upgraded to high-octane gasoline utilizing four-stage adiabatic packed bed reactors containing metal modified beta-zeolite catalyst. In this pathway, the reactor system has inter-bed cooling, and heat is captured as low-pressure steam.[42]

Liquid/Liquid Separations

Attendees noted that to optimize value of liquid products from upgrading, liquid/liquid separations need to be addressed. The report authors note that advanced technologies for thermochemical upgrading of syngas to liquid fuels have addressed the challenge by seeking higher selectivity to single-product streams.[43] Currently, BETO is also supporting the Bioprocessing Separations Consortium, which is applying R&D for solving a variety of separations challenges in biomass conversion.

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[41] Shell developed a gas-to-liquids plant with capability to produce 140,000 barrels of liquids per days in Qatar. The development cost is estimated at $18–$19 billion and took over 30 years to scale. http://www.shell.com/about-us/major-projects/pearl-gtl/pearl-gtl-an-overview.html

[42] Eric C. D. Tan, Michael Talmadge, Abhijit Dutta, Jesse Hensley, Josh Schaidle, Mary Biddy, David Humbird, et al., *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction* (Golden, CO: National Renewable Energy Laboratory, March 2015), NREL/TP-5100-62402, https://www.nrel.gov/docs/fy15osti/62402.pdf.

[43] Eric C. D. Tan, Michael Talmadge, Abhijit Dutta, Jesse Hensley, Josh Schaidle, Mary Biddy, David Humbird, et al., Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction (Golden, CO: National Renewable Energy Laboratory, March 2015), NREL/TP-5100-62402, https://www.nrel.gov/docs/fy15osti/62402.pdf.

Non-Biological Upgrading of Intermediates Opportunities

Biological–Thermocatalytic–Electrochemical Interface

Attendees, especially from thermocatalytic and electrochemical backgrounds, were excited about the potential to tackle an interfacial catalytic grand challenge: the biological–thermocatalytic–electrochemical interface. With the right catalysis strategy, new scaling relationships (as opposed to known scaling of reactors used in biorefineries or petrochemical refineries) could be developed, which could prove appropriate for the logistics needed for engineered carbon reduction. Attendees were optimistic that there are known technologies for upgrading intermediates if the C_1 precursors are generated.

Catalytic Upgrading to Liquid Fuels and Chemicals

Forming carbon-carbon bonds from reduced CO_2 to produce chemicals between C_5 and C_8 provides an opportunity for direct use as transportation fuels. Non-biological conversion specialists believe that a biorefinery could potentially use CO_2 as a feedstock, perform biological reduction, and then convert to liquid fuels catalytically.

Shared Learning from Chemical Industry

Carboxylic acids and light olefins are high-volume chemical commodities. Attendees were interested in bringing in chemical industry stakeholders to share their experience and infrastructure in creating value from the reduced carbon intermediates.

R&D Funding Designs

Attendees said there could be partnership opportunities related to funding opportunity announcements and Small Business Innovation Research awards across universities, national laboratories, and businesses of all sizes. A joint funding award could improve the overall efficiency of a reactor, reaction, catalyst, or process, especially if multiple awards were funded to avoid bias in technology selection.

Though there were more voices expressing support for non-biological reduction and biological upgrading, other attendees said that one possible short-term success would be collaboration between non-biological upgrading experts (with experience in methane upgrading) and biological CO_2 reduction technology developers (with experience in methane production from CO_2). Another initial opportunity could be collaboration between a large corporation that upgrades syngas to liquid fuels and a research partner in CO_2 reduction. Participants suggested that BETO has the capability to operate in this area at the foundational level, but mechanisms would be needed to engage public-private partnerships for scaling up.

Intermediates Market Analysis

Attendees believed there is an opportunity to understand and address the market of reduced carbon intermediates. They stated that a market analysis of formic acid would help drive research. The report authors note researchers have proposed a "formate bioeconomy."[44] BETO has supported market analysis of biomass chemicals, for example *Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential*.[45]

Standards Development

This is an opportunity to engage with the standards development community, such as international fuel standards developers and electrical grid decarbonization policymakers. DOE's Office of Electricity Delivery and Energy Reliability is active in several opportunities for advanced grid R&D, including smart grid R&D and energy storage.[46]

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[44] Oren Yishai, Steffen N. Lindner, Jorge Gonzalez de la Cruz, Hezi Tenenboim, and Arren Bar-Even, "The Formate Bio-Economy," *Current Opinion in Chemical Biology* 35 (2016): 1–9, http://www.sciencedirect.com/science/article/pii/S1367593116300965.

[45] Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin, *Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential* (Golden, CO: National Renewable Energy Laboratory, March 2015), NREL/TP-5100-65509, https://www.nrel.gov/docs/fy16osti/65509.pdf.

[46] "Advanced Grid Research and Development," U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, https://www.energy.gov/oe/mission/advanced-grid-research-and-development.

Enhancing Grid Reliability and Resiliency through Innovative Energy and Carbon Management

Large-scale and rapid deployment of renewables, such as wind and solar power, is driving down both the price of carbon intensity of power, which is good; however, the dynamic and somewhat unpredictable nature of renewable power production can create challenges for efficiently accommodating these resources on the grid. Disparities in power production and demand can cause large electricity price fluctuations and require additional fossil fuel capacity for standby. These challenges could be managed through curtailment and storage of excess electricity, but large-scale deployment of traditional battery storage would be costly and has been slow. However, novel strategies to actively leverage excess renewable power to reduce CO_2 and to store energy in carbon-hydrogen (C-H) bonds were discussed during this workshop. Such strategies would serve multiple valuable functions simultaneously. Namely, excess electricity storage in C-H bonds would enhance grid reliability while increasing the accommodation of renewables on the grid and avoiding CO_2 emissions to the atmosphere.

One such approach discussed during the workshop was a technology developed by Electrochaea, an Israeli company, and demonstrated in Denmark, a country with substantial renewable wind power generation. Electrochaea's technology leverages excess renewable electricity to convert waste derived CO_2 into methane, a form of renewable natural gas. The strategy works by turning on when excess renewable electricity is available and turning off when it is not. During times when excess renewable electricity is available, electricity is used to hydrolyze water into pure streams of H_2 and O_2. Hydrogen produced from the hydrolyzed water is fed into an operating anaerobic digester processing organic waste. Microbial communities in the digester mediate a biochemical reaction between the H_2 and CO_2 to generate methane, which is amenable for addition to the natural gas pipeline and can be used to generate electricity later when renewable power is not available.

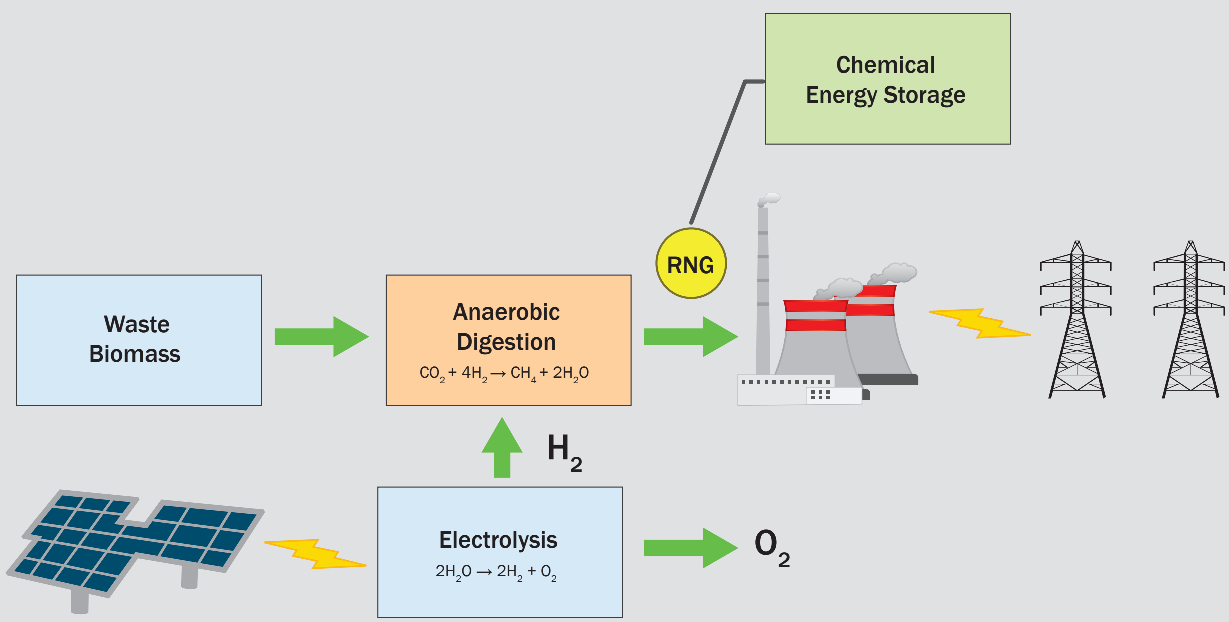

Figure 6. Process for enhancing grid reliability and resiliency through innovative energy and carbon management

Life-Cycle Analysis and Resource Assessment

Multiple attendees suggested the development of LCA and resource assessment studies as an important way to engage stakeholders and improve the perceived value proposition in developing and deploying engineered carbon reduction systems. Publication of more studies and greater information sharing among experts are needed to harmonize assumptions, as well as promoting coordination to achieve common goals for system development and deployment.

Non-Biological Upgrading of Intermediates Needs

Technology-to-Market Planning

Breakout session participants recommended pairing up more projects with established industry partners who have manufacturing capabilities. For example, oil and coal companies and the automobile industry should be engaged to help transform these emerging technologies. This was described was as a "full value chain partnership" project.

R&D Funding

With respect to DOE R&D investment, stakeholders emphasized the importance of providing support for many ideas, rather than being a hub to control technology development. They suggested that an appropriate scale of technology readiness level would be around 1–5.[47] Individuals expressed that large hubs such as the Energy Frontier Research Center have too much overhead operating cost and that smaller organizations such as the Multidisciplinary University Research Initiative are preferable due to relatively less micromanagement. Workshop attendees also support the private sector co-investing with the federal government and suggested that funds such as Breakthrough Energy Ventures should provide financial support for R&D related to non-biological intermediates upgrading.

Policy

Stakeholders recognize the need for policy measures to support the continued technology advancement in this area. The individuals desire a collaborative focus that is most likely to provide a win for everyone involved in the field.

Value Proposition

There is established consumer demand for "green" technology. However, additional analysis is needed to determine whether production processes are economical. Consumer willingness to pay a "green" premium cost on the price of products developed with these technologies also needs to be studied. This type of research can lead to the refinement and utilization of the technology's value proposition.

Carbon Management, Techno-Economic Analysis, Life-Cycle Analysis, and Supply Chain Sustainability Analysis

The technical experts attending the Engineered Carbon Reduction Listening Day also discussed the economic and environmental implications of deploying large-scale non-photosynthetic carbon utilization systems. Traditional renewable biomass supply chains and systems have established techno-economic and life-cycle analyses (TEA and LCA, respectively) approaches, and while rewired systems that bypass land-use requirements and do not proceed with a biomass feedstock could employ many of the same economic and environmental assessment approaches, workshop participants did highlight some differences and unique issues to consider. Additionally, the discussion highlighted unique economic and environmental opportunities that could be created by the large-scale deployment of such systems and indicated a significant need to study and address relevant barriers to private-sector technology deployment.

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47 As of 2010, DOE uses the U.S. Department of Defense definitions for technology readiness level, which can be found at https://www.army.mil/e2/c/downloads/404585.pdf.

The challenges, opportunities, and needs identified by participants broadly fell into four areas:

- Carbon management
- TEA
- LCA
- Supply chain sustainability analysis.

Below, the areas are discussed. In addition to specific challenges, opportunities, and needs, some sections discuss general characteristics identified for the area.

Carbon Management

Opportunities: Tools for Achieving GHG- Reduction Targets

Attendees highlighted the prospects for industrial engineered carbon cycling systems to offer a mechanism for large-scale carbon management, providing a potentially powerful tool for achieving ambitious GHG reduction targets established by subnational and international governments to address climate change. The authors note that beyond the GHG mitigation opportunities highlighted and prioritized by attendees, numerous economic and resource supply chain opportunities were identified and discussed as well. BETO did not seek input on the specific prioritization of the various opportunities and, as an office, may choose to rank these differently than workshop attendees.

Needs: Carbon Management Economic Development Resources

In the near term, attendees suggested public-sector investment in economic development resources for carbon management markets. Specifically, these resources may include test facilities, commercialization infrastructure, and curricula for education and human resources. The test facilities would be sites for technology incubators and involve commercialization partners. Stakeholders also expressed the need for cross-government partnerships to further funding of research, innovation, and information—and especially for developing programs that would label technologies and products as net-zero-carbon.

Needs: Carbon Management Resources

Attendees commented that the economic feasibility of carbon management is greatly impacted by federal policy approaches for guiding carbon management. Stakeholders made recommendations about near-term measures, including incentives for best available control technology (BACT) pathways for air emissions controls, including the suggestion of possible congressional intervention and U.S. Environmental Protection Agency regulation. The R&D community represented at the listening day expressed interest in the creation and demonstration of BACT. BACT would be created and demonstrated, perhaps at test facilities. Another recommendation is to study the price and level of 45Q tax incentives for carbon capture. This analysis needs to be done across diverse groups of stakeholders to ensure cooperation and agreement on underlying assumptions and approach.

Needs: Public-Private Partnerships

Attendees commented about the need to engage existing carbon-related stakeholder groups to understand pinch points and data gaps. Breakout discussions involved enthusiastic interest in a cross-sector approach to public-private partnerships and consortia. These efforts are expected to assist with securing needed R&D resources to bring basic research to the next level of commercialization. Participants also suggested the use of innovation challenges to engage aspiring entrepreneurs.

Needs: Regulatory and Legal Considerations

Regulatory challenges may be discouraging to potential technology adopters. For example, waste CO_2 may not be an applicable feedstock for Renewable Identification Number credits, depending upon its source. In order to overcome this barrier, the exact criteria for defining CO_2 has yet to be standardized legally. Participants suggested that a broader allowance for CO_2 from any source should be included in the U.S. Environmental Protection Agency

Renewable Fuel Standard. CO_2 may be optimal for chemicals, but the Renewable Fuel Standard only provides Renewable Identification Number credits for fuels. Generally, attendees wanted to see more policy for low-carbon fuels and low-carbon products. A price on carbon was missing from current markets.

Techno-Economic Analysis

Challenges: Addressing New System Configurations

While many of the same methods to assess traditional biomass supply-chain and conversion systems will be applicable for rewired carbon cycling systems, some new modeling efforts are required to appropriately consider unique aspects of these non-photosynthetic approaches. Participants said that the cost and carbon intensity of electricity are uniquely sensitive for these new engineered systems, and they suggested that TEA and LCA outputs that identify system viability as a function of electricity price and carbon intensity, respectively, will be critical. Supplemental analysis of job creation potential and opportunities for the distribution of new jobs is also needed. Additional factors, including the quality of the job and the possible local socioeconomic impacts (e.g., jobs in rural areas near ethanol plants or anaerobic digestion facilities and jobs in urban areas near industrial CO_2 sources), should be assessed and quantified. Although near-term availability of CO_2 will dictate viable facility citing and may limit distributed job opportunities, the participants highlighted the profound implications for advancing and deploying direct air capture to enable both distributed job opportunities and a horizontally integrated new carbon economy.

Challenges: End-Product Considerations

CO_2 reduction and upgrading to fuels and products is not the only end use for excess renewable power. Such electrons may also be stored in various ways, such as batteries and pumped hydro power. Thus, there needs to be clear valuation of storing renewable power in chemical bonds. If products from CO_2 are considered, analyses are needed to determine which products make the most economic sense.

Needs: Modeling Carbon Management Resources

In general, research funding is needed to conduct modeling of the carbon management industry. In the near term, specific connections and milestones need to be defined to bridge fundamental research to applied research for the successful private-sector deployment of new technology. Listening day attendees suggested that the DOE consider using the Advanced Research Projects Agency – Energy funding opportunity announcements approach, where tech-to-market plans are required at early stages to encourage formation of industry partnerships with academic, national laboratory, and other scientists.

Needs: Socioeconomic Modeling

Within the framework of TEA, stakeholders discussed modeling gaps related to the socio-economic impacts of engineered carbon reduction technologies. Models need to be developed that simulate land-use and nutrient management impacts. One listening day participant suggested reducing technology development uncertainty by utilizing the ACME (Accelerated Model for Climate Energy) model to predict future locations of renewable electricity generation resources.

Needs: Tax Incentives/Policy

Attendees said there needs to be an understanding of regional and national tax incentives/credits. There is also a need for scenario analysis to evaluate the effects of carbon pricing. Attendees discussed extending the 45Q tax credit for CO_2 capture to CO_2 utilization, as well as the need for a price on carbon to drive innovation.

Needs: Quantifying CO_2 Production

Attendees discussed the need for more precise, reliable system studies to quantify CO_2 production, the best conversion technologies for specific industrial waste or CO_2 streams, and where to site facilities as a function of CO_2 quantity and quality. One key factor participants highlighted, at least for the near term, is the proximity of the

CO_2 source to both cheap and abundant renewable electricity. Early assessments should specifically identify carbon intensity ranges for electricity that allow products to reduce GHG emissions by defined targets (LCA)[48] and price ranges for electricity that allow for system profitability (TEA).[49]

Near-term assessments of systems capable of curtailing excess electricity would help characterize the potential for engineered CO2 reduction strategies to serve as electricity grid stabilization tools. The prospect of leveraging low-carbon power to manage carbon seemed to pique discussion, and attendees noted that such technologies could help address the challenges of managing variability in demand and supply on the grid that result from greater incorporation of renewables such as wind and solar.

Needs: Modeling/Data Inputs

For accurate modeling, data inputs from industry and research sources are needed. Key parameters include the cost of CO_2 and forecasting of renewable power availability and cost. The modeling of CO_2 reduction powered by renewable power is a complex scheme to optimize, so expertise in large-scale energy and economic modeling is needed. Modeling including sensitivity analysis is needed.

The report authors note that the Solar Energy Technologies Office has supported research to evaluate over-generation challenges and to find storage and other solutions.[50] Additionally, the attendees said they would like to see studies on the value of electrolysis enabling temporary energy storage (chemical energy storage), under various scenarios of electricity availability and cost, because it would address such issues related to over-generation and energy storage.

Siting Considerations

The siting of CO_2 reduction and upgrading facilities must take into account several key infrastructure components: (1) the source of the CO_2, (2) the source of (renewable) power, and (3) access to the electrical grid. Attendees noted near-term benefits of siting CO_2 reduction facilities in close proximity to renewable power sources, whether it be a wind farm, solar energy farm, geothermal facility, or hydropower facility, as this could offer opportunities for curtailing inexpensive low-carbon excess electricity. In fact, co-location of the CO_2 reduction facilities at the nexus of various infrastructure components, such as CO_2 and clean power sources, may be needed in the near term to accommodate economic and power carbon intensity realities. As the price and carbon intensity of grid power diminishes, the strict co-localization requirements will be reduced. However, until such critical grid price and carbon intensity thresholds are met, reduction facilities siting may need to align with available infrastructure, and additional costs must be included in the TEA to account for unique system configuration considerations; for example, electric power transmission from the grid, electric power price and carbon intensity variability, and delivery of CO2 should all be considered.

Life-Cycle Analysis

Challenges: Developing Standard Definitions

The purpose of conducting LCA is to confirm that the energy and GHG emissions costs of engineered carbon reduction systems do not exceed the overall energy and GHG emissions benefits of producing fuels and chemicals from reduced CO_2. This is analogous to other BETO sustainability efforts— for example, issues around the impact of indirect land-use change when evaluating bioenergy's environmental benefits. To complete the LCA, definitions

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[48] GHG emissions reduction targets could be selected using those identified in the Energy Independence and Security Act of 2007 for renewable fuels (50% compared to the petroleum baseline for advanced fuels). Carbon intensity ranges could be quantified by varying the assumed electricity input carbon intensity and identifying the maximum electricity carbon intensity that achieves a given GHG reduction target.

[49] Identifying the maximum electricity price for viability will be critical for citing and establishing power agreements for new systems. Participants noted that TEAs identifying a negative electricity price for viability could be expected in the short term, and they argued these results could be used as a proxy for estimating necessary carbon price requirements.

[50] Paul Denholm, Matthew O'Connell, Gregory Brinkman, and Jennie Jorgenson, *Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart* (Golden, CO: National Renewable Energy Laboratory, November 2015), NREL/TP-6A20-65023, https://www.nrel.gov/docs/fy16osti/65023.pdf.

for boundary conditions, storage duration, and functional unit must be stated. While time limited more discussion on the concept and selection of potential functional units, the report authors note that the functional unit is a key characteristic of LCA. The functional unit is used as a reference point to evaluate the entire process life cycle from a defined start to finish; for example, the functional unit could be the life cycle of 1 ton of carbon from a flue gas to a combusted gasoline fuel derived from engineered carbon reduction, or it could be 1 joule of energy from grid transmission to a combusted gasoline fuel derived from engineered carbon reduction.

During the Engineered Carbon Reduction Listening Day, some attendees expressed concern about the life-cycle GHG emissions when industrial waste CO_2 is converted to fuels and combusted since that CO_2 could technically have been derived from fossil inputs. In order to address these concerns, it is critical to define and strictly enforce the use of atmospheric or "waste" CO_2 as the inputs for these systems. Additionally, the carbon intensity and energy efficiency of the entire process needs to be evaluated, as well as the relevant petroleum displacement of the resulting fuels. These same attendees thought upgrading of CO_2 to materials could deliver the best environmental benefits, but they agreed that if the CO_2 inputs were stipulated to be from the atmosphere or a waste stream, then fuel products could substantially reduce the resulting fuel's GHG impact relative to petroleum derived fuels.

Needs: System Design Considerations

Attendees discussed the need for developing flexible LCA approaches to allow for easy adaptation to various system designs and to allow different CO_2 inputs and system configurations to be compared. For example, attendees highlighted the significant differences in overall GHG reductions that could be realized as a function of the CO_2 source, and some questioned the benefits of generating fuels from power plant flue gas as the input carbon would technically be fossil-derived. Ultimately, in these cases, it is critical that the alternate fate of the input CO_2 would have been the atmosphere.[51] If the input CO_2 is a legitimate waste, the petroleum displacement benefits can be quantified compared to the alternate scenario. Any GHG benefits conferred to CO_2-to-fuel systems, regardless of input CO_2 source, would be dependent on the reduction technology, source of electricity, and the calculation of petroleum displacement. Attendees noted that there are likely many scenarios where CO_2-to-products pathways have greater GHG emissions reductions compared to a similar CO_2-to-fuels pathway. Thus, design considerations should consider overall GHG mitigation potential, and possible pathways should not be arbitrarily focused on fuel pathways to the exclusion of others. They also noted that there may be scenarios where the available (perhaps excess) renewable electricity would be better used to enable electrochemical or thermochemical energy storage. Nevertheless, if CO_2-to-fuels pathways were to have viability, attendees stressed the need to get automobile, engine, aviation, and gas turbine manufacturers onboard, with the opportunity for engaging carbon-neutral fuels.

Participants also discussed the implications for establishing bolt-on technologies for carbon mitigation at existing industrial facilities and highlighted the unique opportunity for bolt-on technologies at existing biorefineries specifically. Biorefineries were noted as particularly promising sources for CO_2 since the streams are relatively pure and clean and are expected to increase as the bioeconomy expands. Moreover, carbon utilization of waste biogenic CO_2 from such facilities would serve to enable much lower carbon biomass pathways—even perhaps carbon-neutral or carbon-negative pathways. Industrial non-photosynthetic carbon cycling technologies could serve to rewire the bioeconomy in ways that substantially improve its ability to manage carbon.

Attendees identified an immediate need to expand current biochemical design cases to include reduction and upgrading of fermentation-evolved CO_2. Initial TEA and LCA would be used to identify critical electricity price and carbon intensities needed to achieve economic viability and threshold GHG reductions, respectively. Participants suggested performing some scenarios with carbon prices, as this could be used to tie together TEA and LCA and to identify how rewired systems could offer cost-effective GHG mitigation options.

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[51] If the CO_2 input is derived from fossil sources, it must be the waste byproduct of an established industrial unit generating primary value from that primary purpose. This implies that the alternate fate of the CO_2 input would have been the atmosphere, and the use of the CO_2 in a new process creates additional value that would not have otherwise been realized.

Supply Chain Sustainability Analysis

Opportunities: New Value Chains

Detailed analysis of supply chains will allow the industry to develop a better understanding of relevant markets and to grow a sustainable renewable carbon materials market. Carbon fiber is another market that stakeholders expect to have potential, due to its large market size.

New value chains will also be created due to market demand for engineered carbon reduction technologies. Among listening day attendees, a popular point was that some demand, in the near term, could originate from CO_2 producers and the utility sector, especially if there is excess electricity on the grid at certain times that utility operators need to curtail in order to balance the flow of power. Another unexpected source of demand for these systems may come from traditional fossil fuel producers seeking to identify technologies that would allow them to directly mitigate carbon emissions attributed to their past corporate activities to avoid more costly accountability judgements. Utilities have an opportunity to valorize the excess electricity with energy storage methods, including batteries or CO_2 reduction to fuels.

Attendees commented on needing a roadmap to guide technology development, specifically displaying a suite with several options and approaches to success. Collections of knowledge need to be published.

Opportunities: Value Proposition/Product Diversity

Stakeholders expect that engineered carbon reduction technologies will help change the carbon cycle by increasing the time for carbon recycling. Specifically, products that can quickly lead to increased carbon recycling should be targeted. CO_2-to-product pathways increase the value proposition of engineered carbon reduction technology by producing a commodity without immediate waste (as opposed to combusting a fuel), which provides additional ecosystems services.

Listening day attendees provided suggestions for specific targets for the short term, mid-term, and long term. In the short term, the targets for valorizing CO_2 would include utilizing captured CO_2 from ethanol refineries. This would require studying the actual quality of the fermentation off-gas streams. The target products would be plastics.

In the mid-term, attendees expect an increasingly broad product diversity available and overall higher value proposition. A range of materials, including concrete and carbon fibers, could be produced using waste CO_2. The fertilizer industry presents another opportunity for product development. Certain companies and states that have flexibility and interest in early market adoption would be targeted. In the long term, stakeholders anticipate that CO_2-to-fuels pathways would be feasible after early successes facilitate broader technology implementation.

Summary and Conclusions

Engineered Carbon Reduction Implications

Over the course of the Engineered Carbon Reduction Listening Day, stakeholders reached a consensus that the reduction and utilization technologies discussed have significant potential to impact carbon management and provide economic, environmental, and electric grid stability benefits. A final exercise during the workshop involved summarizing short-term, mid-term, and long-term implications and development targets to integrate engineered carbon reduction technologies into the U.S. energy landscape.

Short Term

Listening day attendees expressed a short-term need for developing and disseminating clearer messaging and educational materials about the impact of CO_2 utilization on job creation, carbon management, and environmental protection. This is an opportunity to establish a carbon management industry where renewable manufacturing and product generation can be effectively separated from land use. Basic research has reached sufficient maturity to begin new applied research projects. There is an immediate need for targeted policy to direct and support new carbon management and utilization industries through strategic carbon pricing and other mechanisms, but stakeholders indicated that new policies would likely follow larger-scale R&D successes rather than stimulate them.

Mid-Term

The mid-term targets suggested during breakout discussions focused on facilitating supply stability by scaling up engineered carbon reduction at biorefineries offering a large, clean and consistent supply of CO_2. Co-location of CO_2 reduction facilities and biorefineries is seen as a promising near- to mid-term opportunity, offering synergies to enhance overall biomass carbon conversion efficiency and to avoid waste.

Long Term

Attendees described some exciting long-term prospects for engineered carbon reduction, characterizing a vision for an entirely new carbon and circular economy enabled, in part, through the broad and strategic distribution of carbon management systems such as engineered carbon reduction systems. Engineered carbon reduction technologies would be scaled accordingly to fit both local sources of CO_2 emissions and CO_2 from direct air capture units, offering the ability to size and control unique supply chains. In fact, attendees noted that direct air capture is a very promising long-term opportunity to not only allow renewable carbon production to be decoupled from the land sector, but also allow for new and perhaps modular fuel and chemical refining capacity anywhere cheap and clean electricity is available. These facilities could be located at military stations and other remote locations. The United States has a strategic need for energy security that can be bolstered by engineered carbon reduction technologies. This is especially true of military use at geographically remote locations where distributing liquid transportation fuels across the globe requires navigating shipping lanes and overcoming weather challenges.

Ultimately, carbon reduction technologies would support a more distributed manufacturing sector with horizontal economics scaled to local CO_2 availability. Distributed manufacturing platforms would promote creation of local jobs. Attendees also expressed a need to develop technologies that would enable the industrialization of carbon management; this would effectively allow for a new carbon management and utilization industry offering renewable carbon feedstocks for all products throughout the economy that currently require fossil-derived petroleum. Attendees further noted that global GHG mitigation needs would require negative-carbon-emission technologies in the long term and that technologies to industrialize carbon utilization would be a valuable tool in achieving ambitious GHG reduction targets. Rewired system outputs would include CO_2-derived products, not just CO_2-derived fuels. Finally, this long-term vision would demonstrate that engineered carbon reduction can be a resource for new industries, new economies, and new jobs along an entire resource supply chain.

BETO Next Steps

The listening day was immediately helpful for the design of a Small Business Innovation Research/Small Business Technology Transfer solicitation, "Engineered Systems for Innovative Wet and Gaseous Waste Valorization: Subtopic B: Non-Photosynthetic Carbon Dioxide Reduction and Biological Intermediate Upgrading."[52] Other next steps are discussed below.

In simultaneous efforts and aided by this stakeholder input, BETO is initiating a carbon reduction and valorization initiative to broaden the potential feedstock portfolio, bypass land-use requirements, explore sustainable carbon utilization strategies, and use existing BETO platforms to produce fuels, chemicals, materials, and other bioproducts. This will be part of the broader Rewiring Initiative that will also seek to identify how cheap and clean power

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[52] Small Business Innovation Research/Small Business Technology Transfer, "Engineered Systems for Innovative Wet and Gaseous Waste Valorization," solicitation, released October 16, 2017, https://www.sbir.gov/sbirsearch/detail/1308625.

can enable new biomass conversion technologies and, more broadly, promote a new carbon and circular economy. The Rewiring Initiative will complement similar CO_2 utilization efforts underway in the DOE Office of Fossil Energy's Office of Clean Coal and Carbon Management, as well as similar ideas outside DOE aimed at deploying carbon-removal technologies.

BETO believes that its Rewiring efforts can improve grid management and enable exportable forms of energy security and storage through chemical bonds. It can also help establish new economic supply chains and make energy more affordable and secure by (1) utilizing existing waste gas carbon resources and inherently deriving more value from existing energy, bioenergy, and biorefinery facilities; (2) reducing the price of CCS by providing a revenue stream outside of 45Q tax credit subsidies; (3) increasing grid flexibility in a system with intermittent renewable resources by providing an outlet for surplus or curtailed electricity; (4) providing distributed feedstock options; (5) building resiliency against fluctuations in biomass resource availability and price; and (6) providing technologies that enable a new carbon management and utilization industry. BETO organized the Engineered Carbon Reduction Listening Day to gather stakeholder input on the state of relevant technologies, as well as advice for future program and R&D directions in this space.

Appendix A: Workshop Agenda

Saturday, July 8, 2017	
8:30 a.m.–9:00 a.m.	Breakfast
	Welcome and Listening Day Overview
9:00 a.m.–9:10 a.m.	**David Babson**, Technology Manager, U.S. Department of Energy's Bioenergy Technologies Office (DOE-BETO)
9:10 a.m.–9:45 a.m.	**Mich Hein**, CEO, Electrochaea LLC *"Charging the Gas Grid with Solar and Wind Energy—From the 'Fat Duck' to Green Gas"*
9:45 a.m.–10:20 a.m.	**Harry Atwater**, Editor in Chief, ACS Photonics *"Artificial Photosynthesis—The Selective CO_2 Reduction Challenge"*
10:20 a.m.–10:40 a.m.	Coffee Break
10:40 a.m.–12:20 p.m.	Panel Discussion: Re-Imagining the Carbon Cycle without Photosynthesis Moderator: **Stephen Mayfield**
10:40 a.m.–11:00 a.m.	**Stephen Mayfield**, Professor, University of California, San Diego, Co-Director, Food and Fuel for the 21st Century Director, California Center for Algae Biotechnology
11:00 a.m.–11:20 a.m.	**Anthony Martino**, Senior Scientist, Sandia National Laboratories *"Sunshine to Petrol: Reimagining Transportation Fuels"*
11:20 a.m.–11:40 a.m.	**Kendra Kuhl**, Opus12 *"Recycling Carbon Dioxide through PEM Electrolysis"*
11:40 a.m.–12:00 p.m.	**William Tumas**, Associate Lab Director of Materials and Chemical Science Technology, National Renewable Energy Laboratory *"Research Challenges for Non-Photosynthetic Solar Fuels Production"*
12:00 p.m.–12:20 p.m.	**Dan Nocera**, Patterson Rockwood Professor of Energy, Harvard University *"Food and Fuel from Sunlight, Air, and Water"*
12:20 p.m.–2:00 p.m.	Lunch
2:00 p.m.–2:30 p.m.	**Harold May**, Professor, Department of Microbiology and Immunology, Medical University of South Carolina *"Reduction of CO_2 by Microbial Electrosynthesis for the Production of Fuels and Chemicals"*
2:30 p.m.–2:50 p.m.	**Jeffery Gralnick**, Professor, Department of Plant and Microbial Biology, Biotechnology Institute at the University of Minnesota *"Driving Microbial Metabolism with Electricity: Challenges and Opportunities in Electrosynthesis"*
2:50 p.m.–3:00 p.m.	Thank You and Closing, DOE-BETO
3:00 p.m.–3:15 p.m.	Coffee Break
3:15 p.m.–6:00 p.m.	DOE-BETO Breakout Sessions (*invite only*)

Appendix B: Workshop Participants

Shota Atsumi
Associate Professor, Department of Chemistry
University of California, Davis

David Babson
Technology Manager
U.S. Department of Energy,
Bioenergy Technologies Office

Katharina Brinkert
Research Fellow
California Institute of Technology

Austin Brown
Senior Analyst
National Renewable Energy Laboratory

Gary Brudvig
Benjamin Silliman Professor of Chemistry and Molecular Biophysics and Biochemistry
Director, Yale Energy Sciences Institute
Yale University

Emily Carter
Dean, School of Engineering and Applied Science
Princeton University

Jae-Soon Choi
Senior R&D Staff
Oak Ridge National Laboratory

Dick Co
Managing Director
Solar Fuels Institute

Pau Farras Costa
Lecture in Inorganic Chemistry
NUI Galway

Noah Deich
Executive Director
Center for Carbon Removal

Heinz Frei
Chemist Senior Scientist, Molecular Biophysics and Integrated Bioimaging
Lawrence Berkeley National Laboratory

Jeffrey Gralnick
Associate Professor, Department of Microbiology
University of Minnesota

Jing Gu
San Diego State University

Adam Guss
Genetic and Metabolic Engineer
Oak Ridge National Laboratory

Amy Halloran
Sandia National Laboratories

Mich Hein
CEO
Electrochaea GmbH

John Holladay
Pacific Northwest National Laboratory

Frances Houle
Senior Staff Scientist, Chemical Sciences Division;
Deputy Director for Science and Research Integration, Joint Center for Artificial Photosynthesis
Lawrence Berkeley National Laboratory

Lauren Illing
Senior Analyst
BCS, Incorporated

Moritz Kuehnel
Senior Research Associate,
Department of Chemistry
University of Cambridge

Kendra Kuhl
Chief Technology Officer
Opus 12

Charles Machan
Assistant Professor of Chemistry
University of Virginia

Yukari Maezato
Naval Research Laboratory

Rahul Malik
Cell Press

Smaranda Marinescu
Gabilan Assistant Professor,
Department of Chemistry
University of Southern California

Anthony Martino
Manager, Materials, Devices and Energy Technology
Sandia National Laboratories

Chris Matranga
National Energy Technology Laboratory

Harold May
Professor, Microbiology and Immunology
Medical University of South Carolina

Ahmad Mia
Fellow
U.S. Department of Energy,
Bioenergy Technologies Office

Chris Mihalcea
Director Fermentation
LanzaTech

Astrid Muller
Laser Technologist, Beckman Institute
California Institute of Technology

Ron Munson
Global Lead – Carbon Capture
Global CCS Institute

Robert Natelson
Senior Technical Research Analyst
BCS, Incorporated

Laura Nereng
Sustainability Leader
3M

Hanieh Niroomand
University of Tennessee

Daniel Nocera
Patterson Rockwood Professor of Energy,
Department of Chemistry and Chemical Biology
Harvard University

Jason Ren
University of Colorado Boulder

Michael Resch
Bioconversion Specialist
National Renewable Energy Laboratory

Edward Rode
DNV GL Group

Ian Rowe
Technology Manager
U.S. Department of Energy,
Bioenergy Technologies Office

Benjamin Rudshteyn
Graduate Student,
Chemistry Department
Yale University

Joshua Schaidle
NBC Thermochemical Platform Lead
National Renewable Energy Laboratory

Brendan Scott
Project Engineer
Allegheny Science and Technology

Hannah Shafaat
Assistant Professor, Department of Chemistry and
Biochemistry
The Ohio State University

Wendy Shaw
Division Director, Physical and
Computational Sciences
Pacific Northwest National Laboratory

Ryan Simkovsky
University of California San Diego

Amanda Smeigh
Assistant Director
Solar Fuels Institute

Alfred Spormann
Professor, Department of Chemical Engineering
and Civil/Environmental Engineering
Stanford University

Joshua Spurgeon
Research Scientist, Solar Fuels Theme Lead,
Conn Center for Renewable Energy Research
University of Louisville

Colleen Tomaino
Manager, Strategic Planning and Analysis
BCS, Incorporated

Bill Tumas
Associate Laboratory Director, Materials and
Chemical Science and Technology
National Renewable Energy Laboratory

Wim Vermaas
Senior Sustainability Scientist, Julie Ann Wrigley
Global Institute of Sustainability;Foundation Professor,
School of Life Sciences, College of Liberal Arts
and Sciences
Arizona State University

Eric Wiedner
Pacific Northwest National Laboratory

Jingjie Wu
Assistant Professor, College of Engineering
and Applied Science
University of Cincinnati

Jenny Yang
University of California, Irvine

Jianping Yu
National Renewable Energy Laboratory

Appendix C: Speaker Biographies and Presentation Titles

Presentation files are available online at www.energy.gov/eere/bioenergy/downloads/engineered-carbon-reduction-listening-day-presentation.

Harry Atwater: "Artificial Photosynthesis—The Selective CO_2 Reduction Challenge"

Harry Atwater is the director at the Joint Center for Artificial Photosynthesis (JCAP) and is a professor of applied physics and materials science at the California Institute of Technology. At the JCAP, Harry and his team are developing a method for using plasmonic metal nanostructures to perform photocatalytic reduction of carbon dioxide (CO_2).

Jeffrey Gralnick: "Driving Microbial Metabolism with Electricity: Challenges and Opportunities in Electrosynthesis"

Jeffrey Gralnick is a professor in the Department of Plant and Microbial Biology and the BioTechnology Institute at the University of Minnesota. He is also one of the leading experts on Shewanella, a type of bacteria found in aquatic environments, and has utilized it to stereochemically convert glycerol to ethanol. Jeffrey's research has led to discoveries in the field of electromethanogenesis.

Mich Hein: "Charging the Gas Grid with Solar and Wind Energy—From the 'Fat Duck' to Green Gas"

Mich Hein is the CEO of Electrochaea LLC, a company that implements a technique to convert CO_2 to methane gas using anaerobic microorganisms. The company makes use of an evolved strain of methanogenic archaea, which demonstrates fast reaction rates and high selectivity in methane production, allowing them to achieve commercial success.

Kendra Kuhl: "Recycling Carbon Dioxide through PEM Electrolysis"

Kendra is the chief technology officer at Opus12, a Berkeley-based technology startup. Kendra and her team are developing processes to leverage renewable power and drive the electrochemical reduction of CO_2 to produce low-carbon fuels and chemicals.

Anthony Martino: "Sunshine to Petrol: Reimagining Transportation Fuels"

Anthony Martino is a senior scientist at Sandia National Laboratories. Anthony is conducting photovoltaic research and—along with other researchers at the national laboratory—proposed a thermochemical conversion of CO_2 and H_2O to CO and H_2.

Harold May: "Reduction of CO_2 by Microbial Electrosynthesis for the Production of Fuels and Chemicals"

Harold May is a professor in the Department of Microbiology and Immunology at the Medical University of South Carolina. Harold is using microbial electrosynthesis to convert CO_2 to produce liquid biofuel, butanol.

Dan Nocera: "Food and Fuel from Sunlight, Air, and Water"

Dan Nocera is a Patterson Rockwood Professor of Energy at Harvard University. Dan created a bionic leaf that replicates the carbon cycling functions of photosynthesis. Dan's process uses CO_2 and hydrogen to generate biomass and liquid biofuels. The bionic leaf is also able to mimic other properties of plants, such as self-healing.

William Tumas: "Research Challenges for Non-Photosynthetic Solar Fuels Production"

William Tumas is the associate lab director of materials and chemical science technology at the National Renewable Energy Laboratory. William is currently involved in solar energy conversion research for electricity and fuel as well as homogeneous and phase-separable catalysis, and waste treatment technology development and assessment.

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