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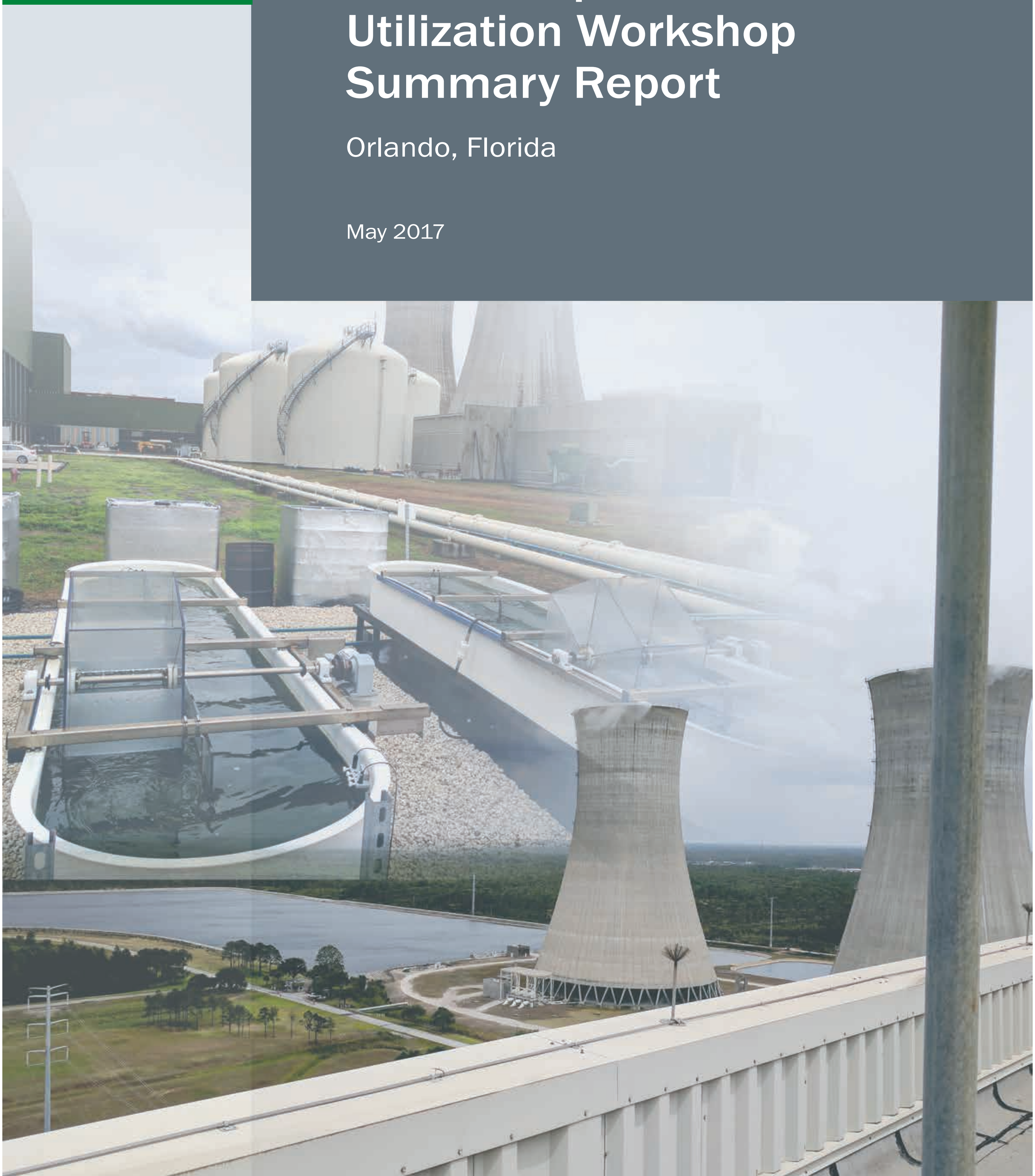
Algae Cultivation for Carbon Capture and Utilization Workshop Summary Report

Orlando, Florida

May 2017



Summary report from the May 23–24, 2017
Algae Cultivation for Carbon Capture and Utilization Workshop
in Orlando, Florida

Workshop and summary report sponsored by the
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

Cover photographs taken at the
Stanton Energy Center, Orlando, Florida

Preface

The U.S. Department of Energy's (DOE's) Bioenergy Technologies Office's (BETO's) mission is to develop transformative and revolutionary sustainable bioenergy technologies for a prosperous nation. BETO's Advanced Algal Systems Program works to lower the costs of production of algal biofuels and bioproducts by funding innovative research and development (R&D) and facilitating partnerships. This report summarizes the results of a BETO-sponsored public workshop held in Orlando, Florida, on May 23–24, 2017.

BETO would like to thank those who participated in the workshop, especially the Orlando Utilities Commission for hosting a project site tour for attendees.

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Introduction

BETO works to accelerate the development of a bioeconomy that can strengthen U.S. energy security, environmental quality, and economic vitality. BETO's Advanced Algal Systems Program (also called the Algae Program) is implementing a long-term applied R&D strategy to support the bioeconomy by lowering the costs of production for algal biofuels and bioproducts. The Algae Program works with partners to develop innovative technologies, integrate these technologies in pre-pilot test environments, and conduct crosscutting analyses to better understand the potential and challenges of an algal biofuels and bioproducts industry. BETO's Algae Program regularly hosts algal biofuels strategy workshops[1] to engage stakeholders in discussions of R&D priorities and to facilitate partnerships.

On May 23–24, 2017, BETO hosted the Algae Cultivation for Carbon Capture and Utilization (CCU) Workshop in Orlando, Florida. Over 80 attendees participated in the event (see Appendix B and Figure 1), providing valuable input through facilitated discussions focused on innovative technologies and business strategies for growing algae on waste carbon dioxide (CO_2) emissions. Representatives from BETO, DOE's Office of Fossil Energy's (FE's) Office of Coal and Power Research and Development, and experts in the fields of waste CCU and algae cultivation considered challenges and opportunities related to the following:

- Sourcing CO_2, including quality, quantity, siting, and transport
- Cultivating algae, including biomass productivity, efficiency in CO_2 utilization, and carbon balances of end products
- Identifying sustainable "win-win" solutions to reducing CO_2 emissions while achieving cost savings.

Resources required for algae cultivation—including CO_2, nutrients, and water—comprise greater than one-third of the cost of producing algal biofuels. Meanwhile, gaseous, thermal, and water waste streams are often financial and environmental burdens on industrial CO_2 emission point sources. Integrating algae cultivation systems into industrial plant operations has the potential to valorize waste streams, synergistically reducing costs for both algal cultivation and waste stream mitigation. Cross-sector, public-private partnerships can help investigate this potential and advance the state of technology for both algal biofuels and CCU strategies funded by DOE.

The industrial partners that BETO and FE would like to engage in exploring these potential synergies include potential CO_2 emitters such as fossil-fired power plants, conventional and cellulosic ethanol biorefineries, cement manufacturers, petrochemical manufacturers, landfills and other sources of biogas, advanced power plants, and wastewater treatment facilities. By bringing diverse stakeholders together, BETO hopes to advance its mission to support a vibrant bioeconomy while also adding value and efficiency to a variety of industries. Participant input from the event, as captured in this report, will help inform DOE strategies for leveraging synergistic opportunities to realize affordable, scalable, and sustainable production of biofuels and bioproducts made from algae.

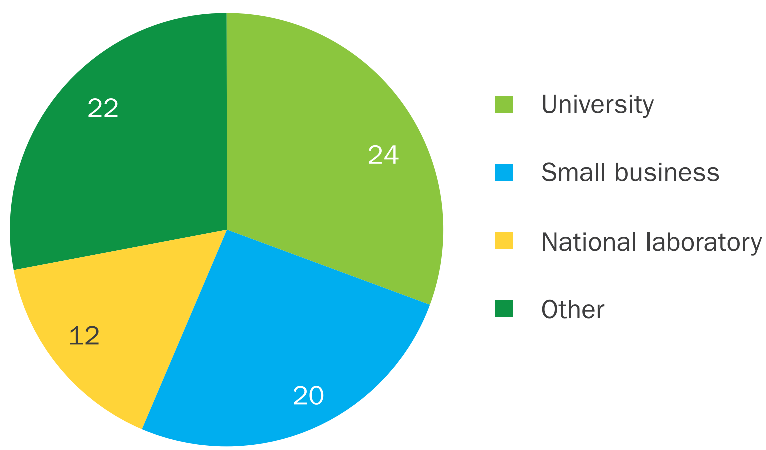

Figure 1. Number of attendees representing affiliated with each stakeholder category

[1] "Algal Biofuels Strategy Workshops," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, accessed June 1, 2017, www.energy.gov/eere/bioenergy/algal-biofuels-strategy-workshops.

Workshop Overview

The workshop opened with presentations from both BETO and FE to provide context on DOE's mission, existing work in the algal biofuels and carbon capture fields, and the goals of the workshop. Following these presentations, the Orlando Utilities Commission presented an overview of its interest in algae cultivation for CCU and their existing algae R&D project located at the Stanton Energy Center's coal-fired power plant, which attendees could tour on day two of the workshop. After invited speakers presented on the state of their R&D, various participants gave 5-minute presentations on topics of interest, including achievements to date, current barriers, and perspectives on the future of CCU broadly and algal CCU specifically.[2] See Appendix A for a detailed workshop agenda.

After laying the framework of the state of technology through these presentations, attendees were divided into five breakout groups for BETO-facilitated discussions.

[2] With the permission of the speakers, presentations are available online: https://energy.gov/eere/bioenergy/downloads/algae-cultivation-carbon-capture-and-utilization-workshop-presentations.

Breakout Session Summaries

Discussion questions within the three breakout sessions followed the path of CO_2 within an envisioned algae CCU system: from CO_2 capture, to delivery to the algae farm, and ultimately to utilization by the algal organisms. Workshop participants also discussed opportunities to coordinate partnerships between algae cultivators and industrial CO_2 emitters, as well as how to best refine various analyses to better communicate these opportunities.

This report is divided into four main topics: (1) Logistics and Siting, (2) Design and Engineering, (3) Identifying Synergies and Coordinating Strategies, and (4) Refining Analyses. Attendees discussed the first topic during the workshop's first breakout session, the second topic during the second breakout session, and the third and fourth topics during the third breakout session. In most of the breakout sessions, attendees were asked to identify potential challenges and opportunities associated with each topic, then brainstorm possible solutions. The key discussion points from these breakout sessions are summarized in the sections below, representing the views of attendees and not necessarily those of DOE.

Logistics and Siting Considerations

Technologies for algae cultivation via industrial CCU present significant challenges related to identifying site locations and facilities with adequate resources to meet operational requirements. Participants defined and discussed these challenges, as well as recommended solutions to overcome them.

Logistics and Siting Challenges

Participants were asked to consider what challenges exist related to CO_2 quality, quantity, concentration, location availability and siting, transport, scaling, and others. Some challenges varied per CO_2 source or type of algae cultivation system, but for the most part the significant challenges were consistent across designs.

CO_2 Quality

Flue gas contains nitrogen oxides, sulfur oxides, and heavy metals. These contaminants vary based on the source of flue gas and even based on the source of the material that generates the flue gas, such as the variety and origin of the coal itself. Contaminant concentrations could prove problematic for companies producing animal feed, nutraceuticals, or other consumables due to potential toxicity or public perception of toxicity, limiting the potential for end products from an algal cultivation facility. Additional gas cleanup steps to purify streams of CO_2 for transfer to algal systems could add costs. Specialized algae culturing techniques may be necessary if contaminants present adverse growth effects. For example, sulfur oxides may increase alkalinity in ponds, requiring the addition of neutralizing agents, such as carbonates. Acceptable pH ranges and contaminant concentrations are strain dependent. For some system designs, these contaminants are negligible and potentially beneficial as micronutrients that can enhance algal growth.

CO_2 Quantity and Concentration

Like quality, CO_2 quantity and concentration vary with the emission source. For example, participants reported natural gas power plants have a CO_2 concentration of 3%–4% in their emissions streams, while coal-fired plants have a concentration of about 10%–13%. Lower concentration streams could present additional logistics and cost concerns to deliver the same amount of gas as higher concentration streams. Participants reported that emissions from biorefineries can be composed of up to 80% CO_2 and could be very attractive to algae cultivators. Pure CO_2 gas would require smaller pipes and blowers than more dilute streams. Higher CO_2 concentration also provides more driving force for mass transfer requirements. Capture, storage, and transport technologies need to match the CO_2 purity requirement of the algae farm. Any temporal variability or potential supply interruptions must be taken into account by the algae cultivators.

Currently, power plants emit more CO_2 than an algae cultivation system could fully utilize. While a power plant could provide all of the CO_2 needs of an algae farm, the farm would have to be thousands of acres to offset facility emissions. One challenge is what to do with excess CO_2, which could potentially lead to ground-level leaking and modification of the air permit of the plant. Excess or emitted CO_2 from the algae farm could present a ground-level environmental release and would need to be sent back to the top of the stack for release.

In addition, algae farms may have to compete with enhanced oil and gas recovery CO_2 utilization applications for access to CO_2 emissions sources, potentially limiting the quantity available in certain locations.

CO_2 Source Locations and Facility Siting

Participants identified land availability for co-location of algae farms with CO_2-generating facilities as a challenge. Algae farms require sites with appropriate topography, access to water and nutrients, climate matched to the algal strain(s), and infrastructure (e.g., roads, rail, power, etc.), in addition to a CO_2 source. Adequate acreage (at least several thousand acres for cultivation system designs at current productivity assumptions) is required to reach economies of scale. Obtaining access to significant acreage will require coordination with diverse landowners, neighbors, local regulatory agencies, and permitting offices. Preparing land for an algal farm can present significant capital costs (e.g., clearing, leveling, digging, lining, etc.). Rail or shipping access is also a siting consideration; logistics requirements should be evaluated in site selection to facilitate easy transport of finished commodity-scale end products offsite. Matching available lands with climate compatibility is a significant consideration when siting algae farms, as well as determining the appropriate algal organism(s) for that area. Water availability is also an important siting consideration. Leveraging recycle streams, as well as wastewater and reclaimed water from the CO_2 source emitter, could be mutually beneficial to the algae producer and CO_2 source.

CO_2 Transport

Distance and method of transportation of the CO_2 to the algae farm is a key issue in the economics of the system. The costs of piping, distribution and control network, compressor power cycling, blowers, trucking, and potential storage requirements all must be considered in the design; companies must minimize costs as well as potential ground-level releases. Developing pipelines will require coordination of easements and crossing rights, which are more challenging for large facilities. Technology advances are needed for carbon-dense storage.

Scale of Process

A challenge for scaling algal cultivation systems is improving algae CO_2 utilization to provide maximum benefit to the emitter. The orders of magnitude difference between algae CO_2 conversion rates and power plant emissions rates translates to significant algae cultivation resource requirements, including land, water, and nutrients. While a high percentage of CO_2 emissions from large CO_2-emitting facilities would not be utilized by an algal farm, the cost per ton of CO_2 for separations is high for a smaller facility or one with lower CO_2 concentrations. Decreasing the cost of capture and compression would help to improve the economics and carbon efficiency of leveraging natural gas power plants and other low-CO_2-concentration emitters. Opportunities to utilize waste emissions for algae cultivation will come from finding an appropriate scale of process. Smaller CO_2-emission sources may be a better match for algae farms in terms of scaling requirements and the percentage of CO_2 the farms are able to capture. There has not yet been a large-scale, non-proprietary demonstration of these integrated technologies, and so additional scaling issues will likely continue to emerge. At stages of increasing scales, replicating laboratory results and research projects into commercial designs is a continued challenge.

Recommended Solutions to Overcoming Logistics and Siting Challenges

Facilitators took the challenges prioritized by each breakout group and asked participants to brainstorm strategies to address them.

Resource Availability

Because algal farms have significant resource requirements, attendees recommended co-locating with as many pre-existing resources as is feasible. Projects should site facilities at locations that have large total land footprints available (at least several thousand acres) near industrial plants that would have the necessary infrastructure, utilities, geographic accessibility, and water resources nearby. Enhancing partnerships among utilities, wastewater facilities, and algae processors will help to facilitate co-location strategies. Creating a network of CO_2 pipelines could benefit algal farms, but this may not be a near-term solution.

Alternative technologies could reduce land requirements. Photobioreactor algae cultivation systems can require less land than open ponds by allowing vertical scaling rather than horizontal. Atmospheric CO_2-capture technologies can expand siting options, especially when partnered with high-alkalinity culturing to efficiently use low-concentration CO_2 streams. Technologies that decouple carbon capture from utilization also can expand siting options. Wastewater holding ponds or existing surface waters could be used for algal growth rather than creating new ponds. Advancements in biomass productivity and CO_2 uptake will also reduce the acreage required for economic viability.

The challenge of scaling facilities can be addressed in part by expanding market entry options via high-value co-products and wastewater treatment services. Geographically diverse pilot plants and testbed facilities could help to refine design requirements by determining the fidelity of process modeling. Modular system designs can also help with scaling; the decision to use large-scale ponds versus modular approaches should be evaluated with regards to economies of scale.

CO_2 Quality

Strategies to address concerns with CO_2 purity and flue gas contaminants can entail either working with algal strains that are able to handle high contaminant concentrations or improving flue gas treatment. Algae farmers could either select for or engineer algae species (extremophiles) that can tolerate a given flue gas composition or opt to adapt native strains growing naturally near the facility. Alternatively, algae farmers could also employ flue gas treatments, such as improved separations, desulfurization, pre-combustion nitrogen removal, and/or installation of heavy metal capture filtration or similar unit processes. The complexity and operating cost tradeoffs between using flue gas and separating a CO_2 stream need to be evaluated. Atmospheric dispersion of CO_2 from open ponds that utilize flue gas also requires additional research.

CO_2 Supply

CO_2 supply variability and interruptions may require algae farms to devise an alternative source of carbon during plant downtime, or will require onsite backup CO_2 storage (involving high purity separation and compression). Application of CO_2 via a bicarbonate buffer solution could reduce interruptions that may be encountered by direct feed. Another way to avoid supply interruptions would be to co-locate an algae farm with a power plant that has more than one unit, as it is unlikely that both would be down simultaneously.

Improving CO_2 consumption efficiency would directly reduce costs by decreasing the amount of CO_2 that needs to be transported and delivered. There are a number of methods for CO_2 transport, and harmonized resource assessments and techno-economic analyses can help make reasonable cost comparisons, which can inform decision making regarding those methods.

When asked what minimum percentage of CO_2 emissions captured by an algae farm would present a beneficial proposition to an emitter, the majority of attendees chose 10%–30%, though answers ranged (Figure 2).

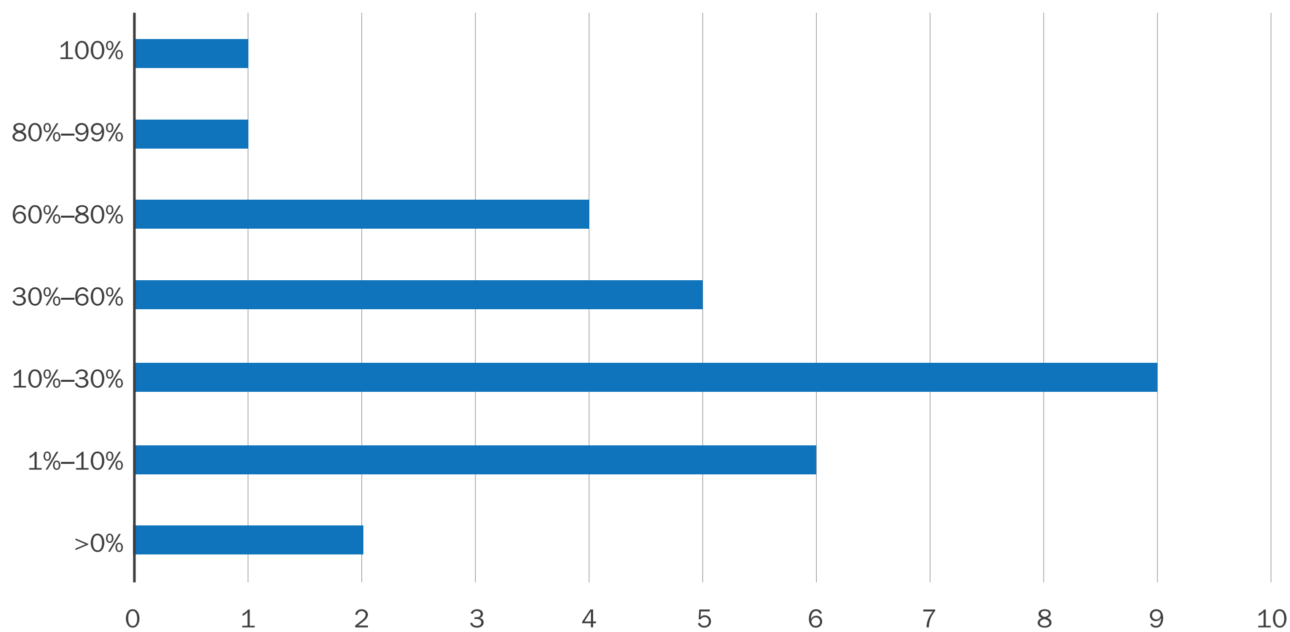

Figure 2. Percentage of CO_2 emissions captured that would present a benefit to an emitter, as indicated via attendee poll

Permitting and Regulations

Permitting requirements and regulations vary from state to state (and often from county to county), and ground level flue gas emissions are prohibited due to their health and safety impacts. Integrated research and analysis into the permitting constraints and technology impacts of algae CCU systems can help to address health and safety concerns, as well as educate regulators. Informing regulators about what changes to the downstream air handling they can expect when adding beneficial reuse via algae cultivation may help to avoid reopening the emitter's air permit. Research and future pilot testing should include improving the biological understanding of the fate of pollutants/components of concern in algae cultivation systems. Strategies that could reduce the risk of permitting issues include bubbling flue gas into a water source and then pumping to the algae ponds, as well as using static mixers to enhance mass transfer by decreasing bubble size. Integrating individual ponds can help to reduce piping and decrease complexity of the system design.

Design and Engineering Considerations

After making decisions regarding siting and resource use, carbon capture and algal cultivation facilities must be designed to maximize efficiencies and minimize costs. Participants discussed these considerations, including transferring the CO_2 into the culture once delivered from the emitter source, as well as improving efficiencies in carbon utilization to maximize biomass production.

Options for Methods To Transfer CO_2 to Algae Culture

Bubbling

Bubbling or sparging compressed CO_2 (or full flue gas streams) into algal cultivation systems has limited transfer efficiency, dependent on the column height, bubble size, and culture temperature. Reducing bubble size promotes better mass transfer efficiency but creates more shearing forces. Workshop participants reported that sparging in traditional raceways has a typical mass transfer efficiency of less than 50%. Low-efficiency mass transfer results in limited CO_2 adsorption and outgassing, losing CO_2 to the atmosphere. If supplying direct flue gas (i.e., not separating out the CO_2), contaminants could be released at ground level and gas cooling could create an acidic condensate waste product, opening the facility to regulatory issues. Bubbling involves costs related to additional energy requirements, complex control systems, and mitigation of plug biofouling. Large algae farms would require multiple control points.

Bicarbonate Solution

Participants reported that buffered bicarbonate solutions allow for a more efficient liquid-to-liquid transfer to the algae culture media compared to bubbling. Full recovery and reuse is also possible because the carbon stays in solution. Separation from culture medium may not be required if the culture medium itself is recycled. Associated costs include the initial capital installation of the absorber, as well as the energy costs of moving liquids. Nutrient levels must be balanced in these solutions for efficient algae assimilation, and nitrogen sources have different effects on pH stability. For example, nitrate has less of a pH effect than ammonium. If pumping high-alkalinity solutions to ponds, the farm may require organisms that thrive at high alkalinity.

Microencapsulation

Microencapsulation of CO_2 consists of a CO_2-absorbing solvent or slurry encased in spherical, CO_2-permeable polymer shells. The capsules typically have diameters in the range of 100–600 micrometers, greatly increasing the surface area and CO_2 absorption rate of the encapsulated solvent.[3] Slow-release suspensions may be a very efficient delivery method. While slow-release suspensions are currently being researched as an advanced method of carbon capture, associated costs relating to scaling, transport, and material sustainability and stability at the scale required by a commercial algae farm may prove prohibitive at the current early state of technology. Capsules could also potentially block light from the algae or, at a minimum, scatter it.

[3] J. K. Stolaroff, C. Ye, J. S. Oakdale, S. E. Baker, W. L. Smith, D. T. Nguyen, C. M. Spadaccini, and R. D. Aines, "Microencapsulation of Advanced Solvents for Carbon Capture," *Faraday Discussions* 192 (2016): 271–281, doi:10.1039/c6fd00049e.

Membrane Mediated Delivery

Novel membrane technologies have the advantage of no moving parts, resulting in limited maintenance and lower energy requirements. Membranes require a relatively large surface area, control systems, and designated pressure parameters, and are subject to fouling. Additional associated costs include membrane material fabrication and replacement.

Direct Atmospheric Capture

Atmospheric capture of CO_2 would reduce the costs associated with transporting gas from the emission source. This early-stage technology requires more R&D to reduce associated energy requirements and costs and to increase its CO_2 yields and transfer/absorption efficiencies.

Opportunities for Carbon Accounting Strategies

In CCU projects, carbon will have to be accounted for throughout the system to ensure efficient utilization, and it may be a reporting requirement. It is challenging to do this accounting, particularly in an open pond system. Under 40 C.F.R. § 98.RR (for claiming 45Q tax credit[4]) for enhanced oil recovery, the emitter gets the tax credit for the capture, but the enhanced oil recovery operator is responsible for the compliance paperwork to verify that the CO_2 was injected into the ground. An algae system would require a similar verification plan approved by the U.S. Environmental Protection Agency or by the state governing board if the state has primacy. The regulatory purpose of the carbon accounting will drive the methodology. Attendees discussed the following methods for carbon accounting:

Biomass Composition

Biomass produced could serve as direct indicator of CO_2 captured versus lost to algal respiration or abiotic escape from the system. Biomass composition varies depending on culture conditions, organisms, and nutrient availability. Routinely measuring the ash free dry weight of the total biomass produced, along with an elemental analysis or isotope measurement and tracking, can determine the carbon content. The Algae Biomass Organization's technical standards report, *Industrial Algae Measurements*, could help to standardize these measurements.[5]

Mass Balance

Mass balance equations require determination of system boundaries and should be inclusive of the CO_2 emitter. The final boundary will depend on the end use of the algae, whether combusted for fuel, consumed, or sequestered into plastics or other bioproducts. Seasonal variability and other impacts will cause variability in carbon uptake ability; biology is not a steady-state system. Infrared sensors could assist detection of CO_2 in input air streams, and precise ambient air measurements could support accounting for off-gas losses, to input into mass balance equations. A detailed sampling strategy and clear boundary conditions would be required.

Life-Cycle Analysis Modeling

A CO_2 life-cycle analysis (LCA) model of the system design will help improve designs ahead of project build to identify and maximize opportunities for CO_2 efficiencies. Defining LCA methodology, inputs, and assumptions is a challenge, and a multi-product algae farm could potentially require multiple LCAs. While algae can use non-arable land, it is still land intensive. Therefore, there are likely to be indirect land-use and water-use changes to consider when defining model boundaries. The impact of the system depends on both the technology pathway and the individual project site. Making comparisons against a relative baseline for the product being replaced is also difficult. Additional LCA considerations are discussed later in this report.

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[4] U.S. Environmental Protection Agency (EPA), *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions Subpart RR and Subpart UU: Injection and Geologic Sequestration of Carbon Dioxide* (EPA, November 2010), https://www.epa.gov/sites/production/files/2015-07/documents/subpart-rr-uu_eia.pdf.

[5] Algae Biomass Organization (ABO), I*ndustrial Algae Measurements, Version 7.0* (ABO, September 2015), http://algaebiomass.org/resource-center/technical-standards/IAM7.pdf.

Opportunities for Optimizing Efficiency in CO_2 Utilization

One of the areas for system improvement is the efficiency of an algal culture's CO_2 utilization after the CO_2 is delivered to the cultivation system and before harvest. Attendees recommended the following strategies for optimizing this efficiency:

Algal Biology

Improving the algae can optimize carbon utilization efficiency in the system design. Selecting or developing algal strains adapted to the environment and possessing high CO_2 uptake rates and carbon concentrating mechanisms—and thus, high productivity—will improve overall system performance. Approaches such as metabolic engineering, gene enhancement, and systems biology can develop advanced performance strains. Genetically modified algae cultivated outdoors require U.S. Environmental Protection Agency Toxic Substances Control Act Environmental Release Application permitting. Optimizing cultures with designed consortia of algae and other organisms can potentially maximize productivity as well.

Algae Cultivation System

Improvements in the algal cultivation system and growth designs can help to mitigate CO_2 losses and improve consumption efficiencies. Strategies for optimizing growth include the following: improving culture mixing (while acknowledging the tradeoff that, while mixing creates better mass transfer, it requires more energy); providing sufficient sunlight through design of the reactor or pond depth; and installing control systems for pH, temperature, and delivery of nutrients, CO_2, flue gas, or bicarbonate solution. Attendees reported that CO_2 outgassing declines by two orders of magnitude as pH increases from 7.5 to 9.5. Thus, outgassing could be minimized and CO_2 utilization could be maximized by using high-pH-tolerant strains. Sensors and machine learning for cultivation diagnostics and analytics can improve cultivation efficiency and harvesting strategies.

CO_2 Delivery

Coordinating the CO_2 delivery with the demands of the algae cultivation system can help to reduce off-gassing or delivery of unused CO_2, enough to meet maximum growth rate requirements without supplying excess CO_2 to the farm. Strategies such as matching CO_2 delivery to the light in the system and storing CO_2 during non-peak consumption times of day can help to reduce excess CO_2. Separating the algae growth system from the carbon introduction system can help to minimize over-delivery of CO_2. Consistent quality and composition of the CO_2 source, or a pure CO_2 stream, will help improve efficiency of the system—though this may present tradeoffs in the cost of purification equipment (scrubbers). Capturing the off-gas and reusing it and/or recycling carbonate along with water captured during harvesting may be possible in some systems. Throughout consideration of these methods, economic efficiency requirements may outweigh CO_2 utilization efficiency requirements. Future large-scale project demonstrations, in conjunction with numerical modeling of a variety of CO_2-to-pond delivery technologies and operational strategies, will help to evaluate these tradeoffs.

Identifying Synergies and Coordination Strategies

Potential for Mutual Benefit between CO_2 Producers and Algae Producers

This workshop was held in part to identify those areas that present opportunities for collaboration between CO_2 emitters and algae cultivators. The groups determined that power plants (including coal-fired, natural gas, and combined cycle), biogas facilities, biorefineries, and cement plants could potentially benefit from arrangements with algae producers, and vice versa. There are many considerations that would factor into decision making about CO_2 sources; however, when asked which CO_2 source makes the most sense for a commercial algal biofuels company in terms of quantity, quality, and cost, participants ranked coal-fired power generation facilities the highest (Figure 3).

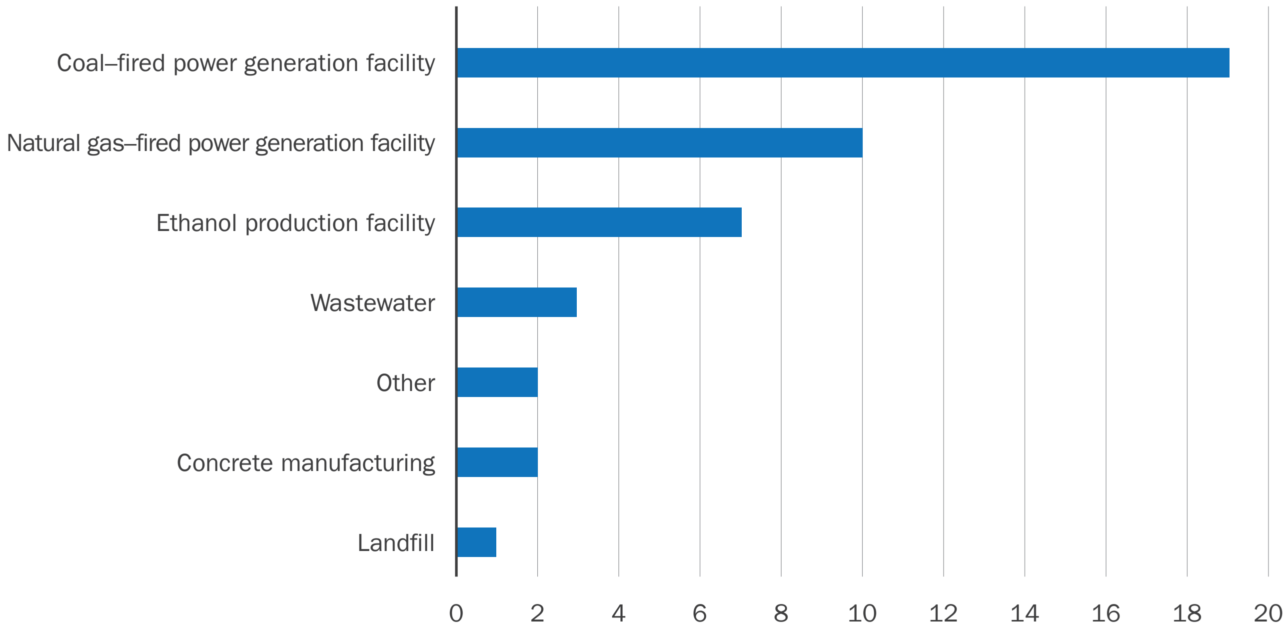

Figure 3. Recommended emission sources, as indicated via attendee poll

The breakout groups discussed the following mutually beneficial opportunities for these groups:

Valorizing Waste

One of the most direct opportunities is the potential for point source CO_2 emitters to valorize system waste by selling flue gas and/or waste CO_2 streams to algae cultivators. Some states and regions have initiated carbon trading programs that could support these arrangements for the power producer. If a carbon emitter chooses to co-locate and own an algae facility, it could directly benefit from the commoditization and sale of algae products, including, in the near-term, fertilizer and other bioproducts. Marketing to utility providers and consumers as a "green" product could bring emitters additional value from the valorization of waste, capitalizing on the demand for renewables in the power sector that is emerging in many regions. Communicating the environmental benefits of reuse of carbon could improve public relations between stationary CO_2 sources and the public.

Algae farms, potentially in coordination with CO_2 emitters, could also partner with confined animal feeding operations to leverage animal waste as a nutrient supply. Similarly, aquaculture facilities, such as those that grow shrimp and catfish, could provide nutrients for algae production and then use algae components (such as omega-3 fatty acids and protein) as feed, potentially improving the sustainability of the fish farm and enabling the remaining lipids to be converted into bioproducts and fuel intermediates.

Opportunity for Rural Jobs

Areas with enough land available to cultivate algae would also likely benefit from rural job development programs, such as the U.S. Department of Agriculture's Rural Development workforce programs. Public utilities could benefit in siting negotiations from being able to provide additional jobs to a region in aquaculture of algae and applied engineering, in addition to plant operation and maintenance. Public-private partnerships could help to foster regional economic development. Creating algae CCU industrial and manufacturing hubs around CO_2 point sources could potentially strengthen local economies, attract new business, and increase the attractiveness of a region to a skilled labor force.

Onsite Water Treatment

CO_2 emitters also face regulatory requirements with regard to water cleanup and could use algae to improve the water quality of onsite cooling ponds and other reservoirs. National Pollutant Discharge Elimination System regulations for watershed discharge allowances could also be addressed with purpose- or naturally-grown algae systems.

Shared Resources

Many CO_2-emitter facilities have more to offer algae cultivators than just the CO_2 stream. Co-location could consolidate utility requirements, staff, and transportation access systems, including railways and freights. The transportation that brings in coal or other material for thermal processes can bring the biomass or biofuel intermediate back out of the facility and toward a refinery. The algae farm could use waste heat from the plant as energy for drying or other power requirements. Micronutrients and metals within flue gas streams could also provide growth enhancement for algal cultures, as could digester effluent from biogas facilities. If the site also integrates wastewater treatment, nutrients in the waste stream could be used for algae cultivation as well. Attendees recommended that algal biomass could potentially be co-fired in existing power facilities, such as coal-fired power plants, and reduce the percentage of CO_2 capture requirements for the producers.[6] Cooling water may be too warm for direct discharge into waterways. Algae cultivation may provide opportunities for value-added cooling.

Biogas

A novel synergy is the potential for algae to "clean up" the CO_2 from biogas facilities and enable them to have a purified, more valuable methane stream. Facilities that generate biogas, which contains approximately 30%–40% CO_2, could be used to cultivate algae with nutrients supplied by digester effluent. Then, the algal biomass could be added as a feedstock to the digester for methane production.

Recommendations for Facilitating Partnerships

Facilitating coordination between algae producers and CO_2 emitters may best be accomplished by leveraging power generation trade groups (e.g., American Public Power Association, Electric Power Supply Association, Electric Power Research Institute, etc.). Many generators may not realize the diversity of potential opportunities for beneficial CO_2 reuse, and providing them with information and resources (and potentially a full outreach campaign) could accelerate innovation in this area. Providing techno-economic analyses to the management board of the emitter and illustrating the financial opportunities of a "circular economy"[7] could help facilitate discussions of partnerships. Engaging the senior management of a utility could help to change corporate attitudes from perceiving this R&D as a "cost" to recognizing it as an "investment."

A quantitative resource assessment mapping algal biomass potential to wastewater facility locations and point source CO_2 emitters—especially highlighting when they are both available—would help algae producers negotiate siting opportunities. Industry- or government-sponsored modeling efforts and workshops could continue to help foster dialogue between these two industries. Engaging across the government to include the U.S. Department of Agriculture and local rural development offices could help garner the support of a broader audience.

Ultimately, algal biofuel technologies will have to move up in technology readiness level to gain the interest of partnering companies.

Refining Analyses

To evaluate the potential for algae CCU strategies, robust multi-level analyses are needed to answer whether technologies will scale, if they will provide economic value, and whether they will be beneficial to environmental health and sustainability. Participants discussed reasonable boundaries and assumptions for various analyses and identified existing data and information gaps that must be filled to answer these questions.

[6] In May 2015, BETO hosted a Bioenergy with Carbon Capture and Sequestration Workshop that covered the co-firing of biomass. For more information, visit the workshop web page: https://www.energy.gov/eere/bioenergy/bioenergy-carbon-capture-and-sequestration-workshop.

[7] A circular economy model aims to maintain the value of materials, products, and resources in the economy as long as possible to maximize their value and minimize waste.

Techno-Economic Analyses

Techno-economic analysis models calculate the capital and operating expenditures of a system to arrive at total system costs and the price of final products. Standardization of these models helps to assess performance against the state of technology and determine natural scalability price breakpoints. To standardize these analyses, agreement on boundary conditions is needed, including return on investment, land values, financing costs, biomass cost limitations, and resource cost curves. Techno-economic analyses require algae compositional data (component and elemental) with high mass closure, engineering detail on CO_2 capture and transport approaches, information on CO_2 consumption efficiencies, data on dewatering technologies, and cultivation yield data inclusive of carbon and nutrient recycling. Organism compositional analysis (as standardized by the Algae Biomass Organization's technical standards) is needed to provide input on final product values, though current compositional and omics data is incomplete for many organisms.

For techno-economic analyses, the boundary for algae CCU systems should include production of CO_2 through to the end products. Market analysis and projections can provide values to make determinations about final targeted products, comparing replacements with novel product entry points based on market volume, value, and elasticity. The financial impacts of regulation (e.g., permitting costs) and policy (e.g., tax rates, financing incentives, and pollution mitigation credit markets) are typically held constant in state of technology comparisons, though they could be integrated for scenario planning. Real options analysis includes predictions on future policy and market conditions, incorporating the predicted and desired lifetime of a facility. Modeling can also evaluate the impact of algae CCU technologies on the economy, incorporating scales of process and number of facilities in a region to determine job creation versus displacement figures, indirect jobs created, and revenue for a local economy.

Life-Cycle Analyses

LCAs account for greenhouse gases within a system and can include evaluations of water consumption and nutrient use. Comprehensive LCA boundaries should include the greenhouse gases produced by the energy demands for CO_2 capture and transport. The energetics for carbon capture, primarily parasitic energy load for new carbon capture systems being developed, needs to be better understood, as does compressor operation/logistical constraints for 24-hour power demand. Like techno-economic analyses, the boundary for LCAs of algae CCU systems should include the production of CO_2 through to the end products (and potentially to the end of product life) and should account for recycle systems. When assessing the benefits of an algae CCU system, final product substitution should be accounted for—for example, algae fertilizer displacement of fossil nitrogen fertilizer. Water and fertilizer (direct and indirect) consumption per ton of biomass or amount of product (e.g., gasoline gallon equivalent) should be calculated within an LCA. Water stress analysis can help to refine water calculations to assess water demands against water available, as some regions may have water scarcity concerns. Land-use change can also be accounted for within LCAs, assessing putting marginal lands to productive use. LCAs should reference consistent baseline cases, typically those of nonrenewable energy assumptions about emissions.

Resource Assessments

Resource assessments for algal biomass cultivation evaluate demands for land, water, nutrients, and other inputs over the projected lifetime of farm operations, as well as geospatially map locations able to support those demands. Data and assumptions regarding minimum cultivation area requirements, hourly CO_2 emissions at a site scale, flue gas characterization, and waste heat potential are needed for algal CCU resource assessments. Mapping the availability of wastewater treatment facilities and smaller CO_2 emission sources can help to identify co-location opportunities.

Conclusions

Strong economic, environmental, and societal value propositions drive interest in collaboration between industrial CO_2 emission sources and the algae industry. Initial research and collaboration in this space has yielded promising results; however, more fundamental R&D is needed to realize the scale of opportunity. Through their discussions, workshop participants unveiled a framework that supports federally funded research on the unknowns and opportunities important to both partners, the point source and algae facility.

Overall, discussion from the workshop participants highlighted multiple areas of work that could support realization of algae as a CO_2-utilization platform. Advancements in this field of study will be made by investigating—under system-relevant conditions—engineering and business strategies that address the differential in the scale of CO_2 emissions and cultivation requirements and CO_2 transportation from point source to cultivation. These strategies must be compliant with local air and water regulatory standards. Investigating and integrating process and chemical strategies is necessary to reduce risk, as this can ensure that even when one partner is offline, the other can utilize carbon emissions.

Many point sources can benefit from using algae as a CO_2-mitigation strategy. Therefore, from an R&D perspective, it is important to propose system designs that enable source-agnostic technologies that are cost-effective and biologically efficient, especially for dilute source streams. Likewise, while multiple options for delivering CO_2 to cultivation systems have been investigated, continued research with materials and integration from point sources is needed. At the same time, it is important that research demonstrates that the algae crop and cultivation operations can perform consistently on real-world emissions, as they will vary in composition of constituents.

Since both members of the partnership seek benefits from collaborating on CO_2 utilization, analyses and carbon accounting plans need to encompass both systems. Mass balance, LCA, and biochemical composition analysis will factor in case-specific parameters like the cultivation system, algae product regime, and local, state, and federal reporting requirements for environmental compliance or incentives.

Workshop participants frequently expressed that research partnerships need to be integrated in real-world conditions with local partners. To expand partnerships, the algae industry would benefit from increased communication of the value proposition of algae CO_2 utilization to nontraditional stakeholders in the bioeconomy. Expanded communication could lead to technical collaboration efforts that may uncover new synergies and research questions between these groups. Third-party modelling efforts could assist in fostering connections, especially with nontraditional bioeconomy stakeholders.

The field must communicate what resources CO_2 emission point sources need in order to take advantage of algae as an emissions mitigation strategy. These resources reflect that algae cultivation is an agronomic practice and include expansive and relatively flat land availability, favorable climate, access to infrastructure to distribute algae products, and water resources with sufficient quantity and quality such that algae cultivation will not result in environmental impairment.

Because of the opportunity for algae feedstock to utilize non-arable land (in addition to CO_2) and remediate reclamation and impaired waters, as well as to support rural development, the feedstock is of interest to utilities, water regulatory bodies, and economic development boards. Based on the discussions from this workshop, R&D that is focused on using systems-relevant materials and is conducted with partners who believe they will benefit from having an algae industrial partner will help to realize the value proposition of algae CO_2 utilization.

Appendix A: Workshop Agenda

Time	Agenda Item	Speaker
Algae Cultivation for Carbon Capture and Utilization U.S. Department of Energy, Bioenergy Technologies Office *May 23–24, 2017 | Orlando, FL*		
Tuesday, May 23, 2017 *Subject matter experts will meet to discuss carbon dioxide capture and utilization (CCU) applicability to algae cultivation for the production of biofuels and bioproducts. Following presentations from the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office and Office of Fossil Energy, as well as project performers, participants will break into small groups to share information about the state of this technology and the challenges that must be addressed to achieve commercial-scale systems.*		
Time	**Agenda Item**	**Speaker**
8:15 a.m.–8:30 a.m.	Welcome and Introduction: DOE Bioenergy Technologies Office	Christy Sterner, Bioenergy Technologies Office
8:30 a.m.–8:45 a.m.	Introduction to Collaboration Platform	Lauren Illing, BCS, Incorporated
8:45 a.m.–9:00 a.m.	Introduction: DOE Office of Fossil Energy	Lynn Brickett, National Energy Technology Laboratory
9:00 a.m.–9:15 a.m.	Orlando Utilities Commission Interest in CCU	Robert Teegarden, Orlando Utilities Commission
9:15 a.m.–9:30 a.m.	Overview of ASU Project Work in CCU	Thomas Dempster, Arizona State University
9:30 a.m.–9:45 a.m.	Overview of Global Algae Innovations Project Work in CCU	David Hazlebeck, Global Algae Innovations
9:45 a.m.–9:55 a.m.	Break	
9:55 a.m.–11:45 a.m.	Open Forum Presentations	Five-minute briefings from pre-selected participants on topics of their interest. Suggested focus on achievements to date, current barriers, and outlook for the future of CCU and algal CCU.
11:45 a.m.–12:45 p.m.	Lunch	
12:45 p.m.–2:15 p.m.	Breakout Session 1: Logistics and Siting Considerations	
2:15 p.m.–2:25 p.m.	Break	
2:25 p.m.–3:55 p.m.	Breakout Session 2: Design and Engineering Considerations	
3:55 p.m.–4:05 p.m.	Break	
4:05 p.m.–5:35 p.m.	Breakout Session 3: Assessment of Potential Commercial Application and Identifying Synergies	
5:35 p.m.–5:45 p.m.	Closing Summary for Day 1	Christy Sterner, Bioenergy Technologies Office
Wednesday, May 24, 2017 *Report outs from breakout sessions followed by a project site tour.*		
8:50 a.m.–9:00 a.m.	Convene	Christy Sterner, Bioenergy Technologies Office
9:00 a.m.–11:30 a.m.	Plenary Report Outs and Group Discussion	Breakout Session Rapporteurs
11:30 a.m.–11:45 a.m.	The Orlando Utilities Commission Algae CO_2 Utilization Project	Tryg Lundquist, MicroBio Engineering
11:45 a.m.–12:00 p.m.	Summary Conclusions and Thank You to Participants	Christy Sterner, Bioenergy Technologies Office
12:00 p.m.–1:00 p.m.	Lunch	
1:00 p.m.–5:00 p.m.	Project Site Tour	The Orlando Utilities Commission Algae CO_2 Utilization Project

Appendix B: Workshop Participants

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