

Carbon Utilization Infrastructure, Markets, Research & Development Bioenergy Technologies Office Perspective on the NASEM Study

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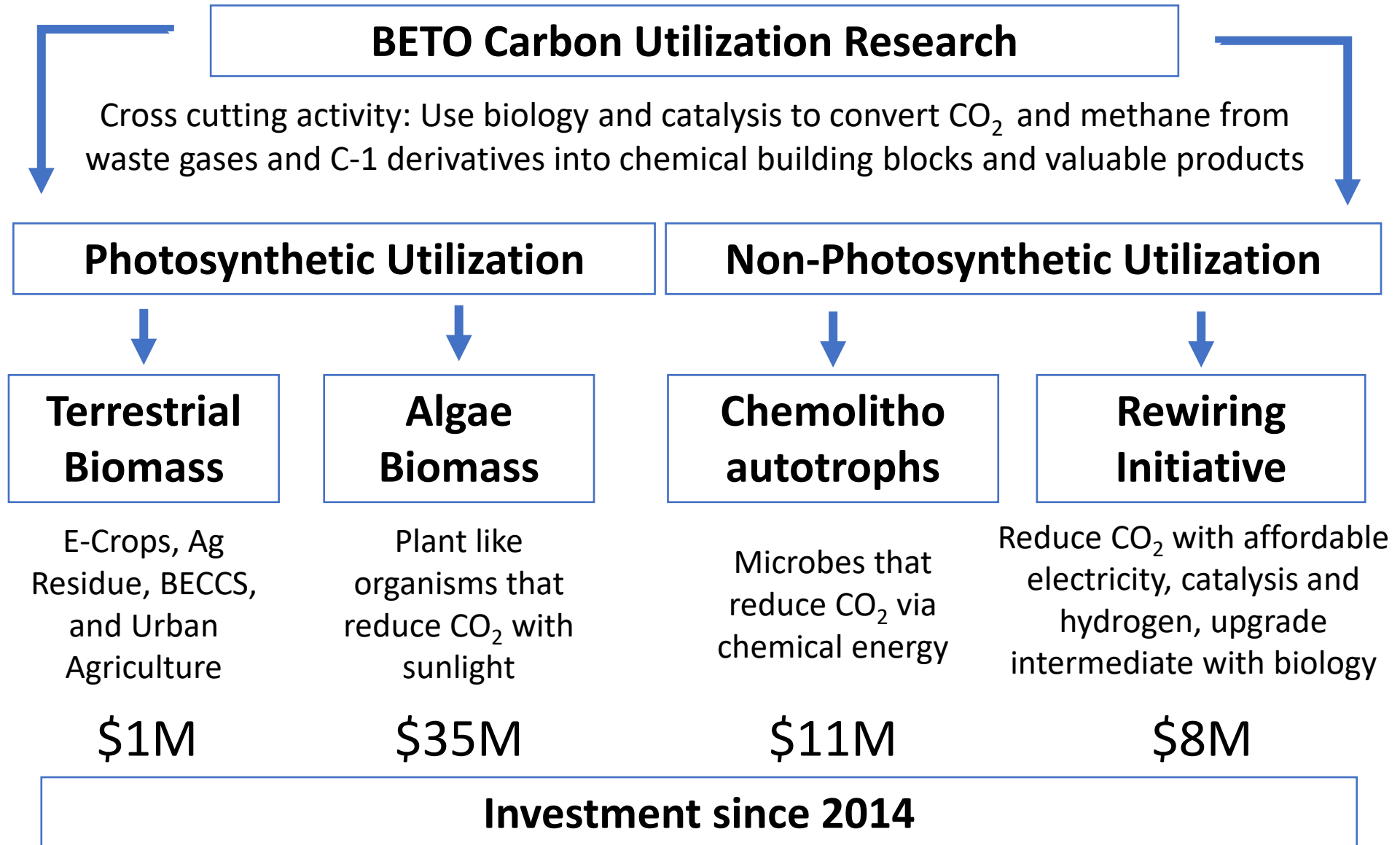
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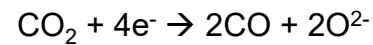
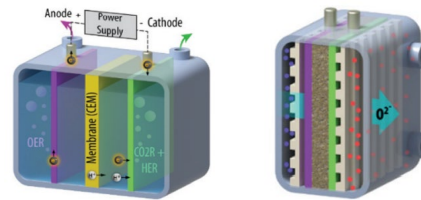
Recycling Gaseous Carbon



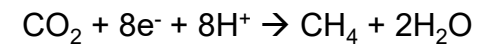
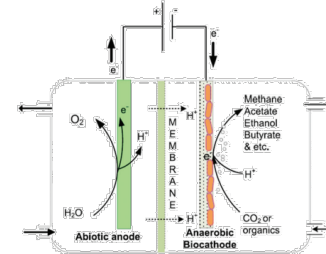
CO₂-to-Fuels Pathways

Direct Conversion:
Direct Utilization of Electricity

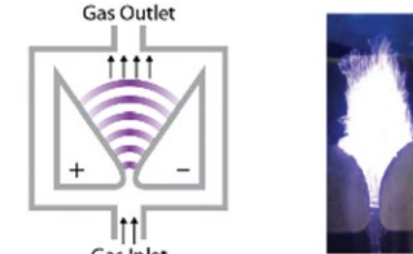
Low and High Temperature Electrolysis



Microbial Electrosynthesis (MES/MEC)

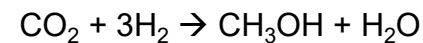
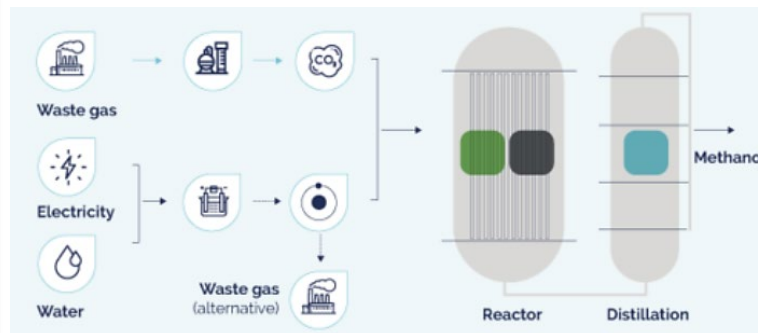


Non-Thermal Plasma Conversion

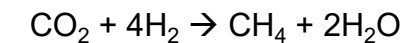
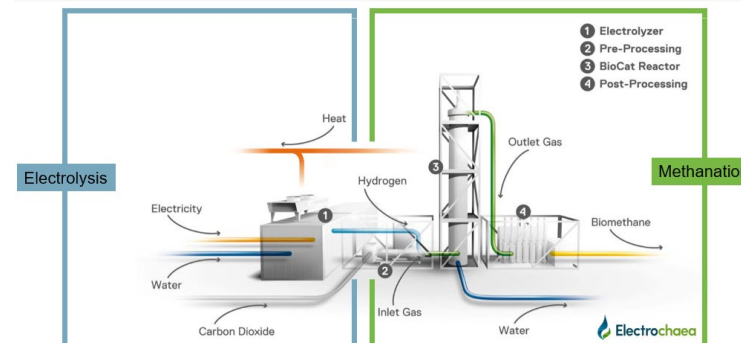


Indirect Conversion:
H₂ Mediated

Thermocatalytic Conversion

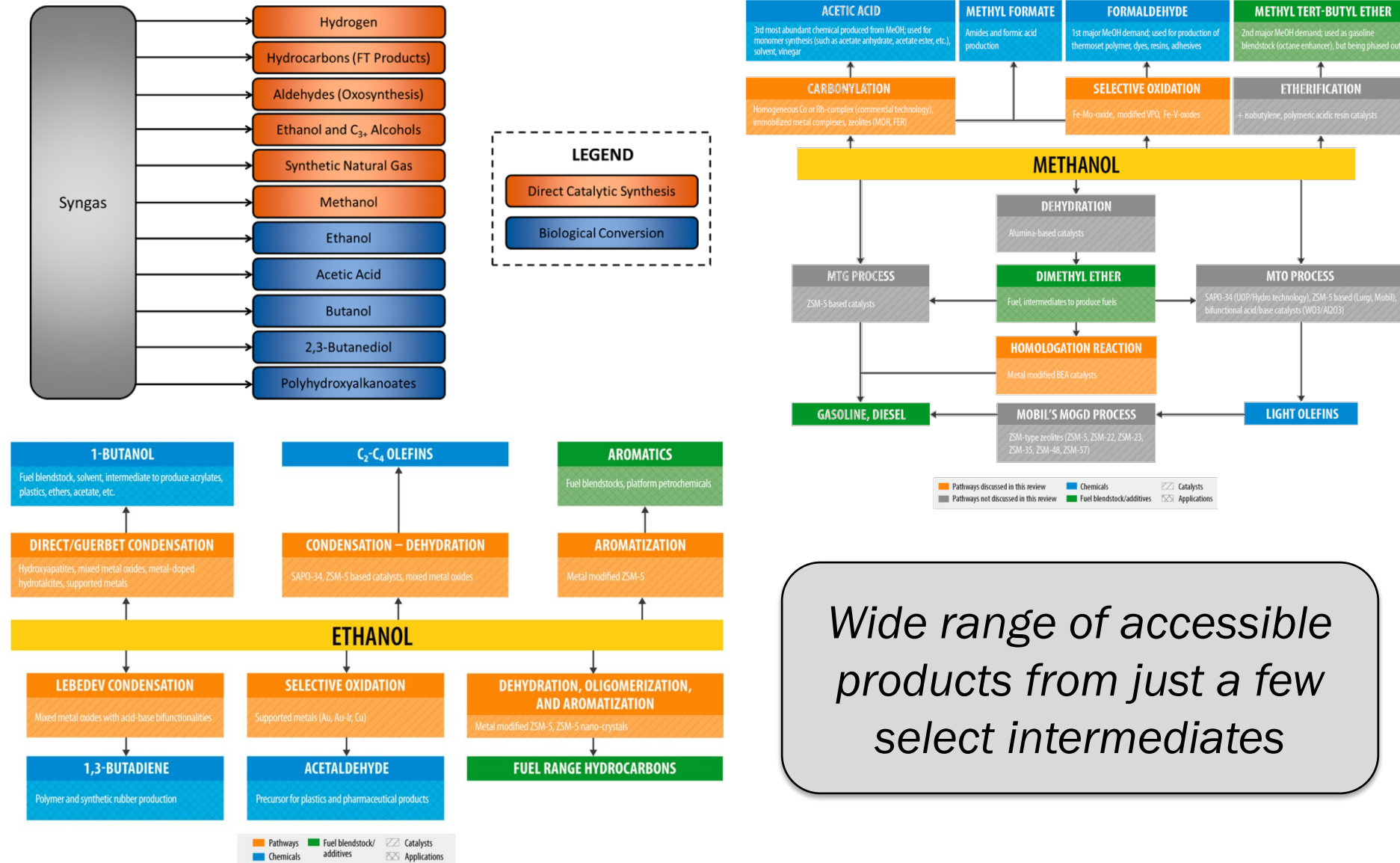


Biological Conversion

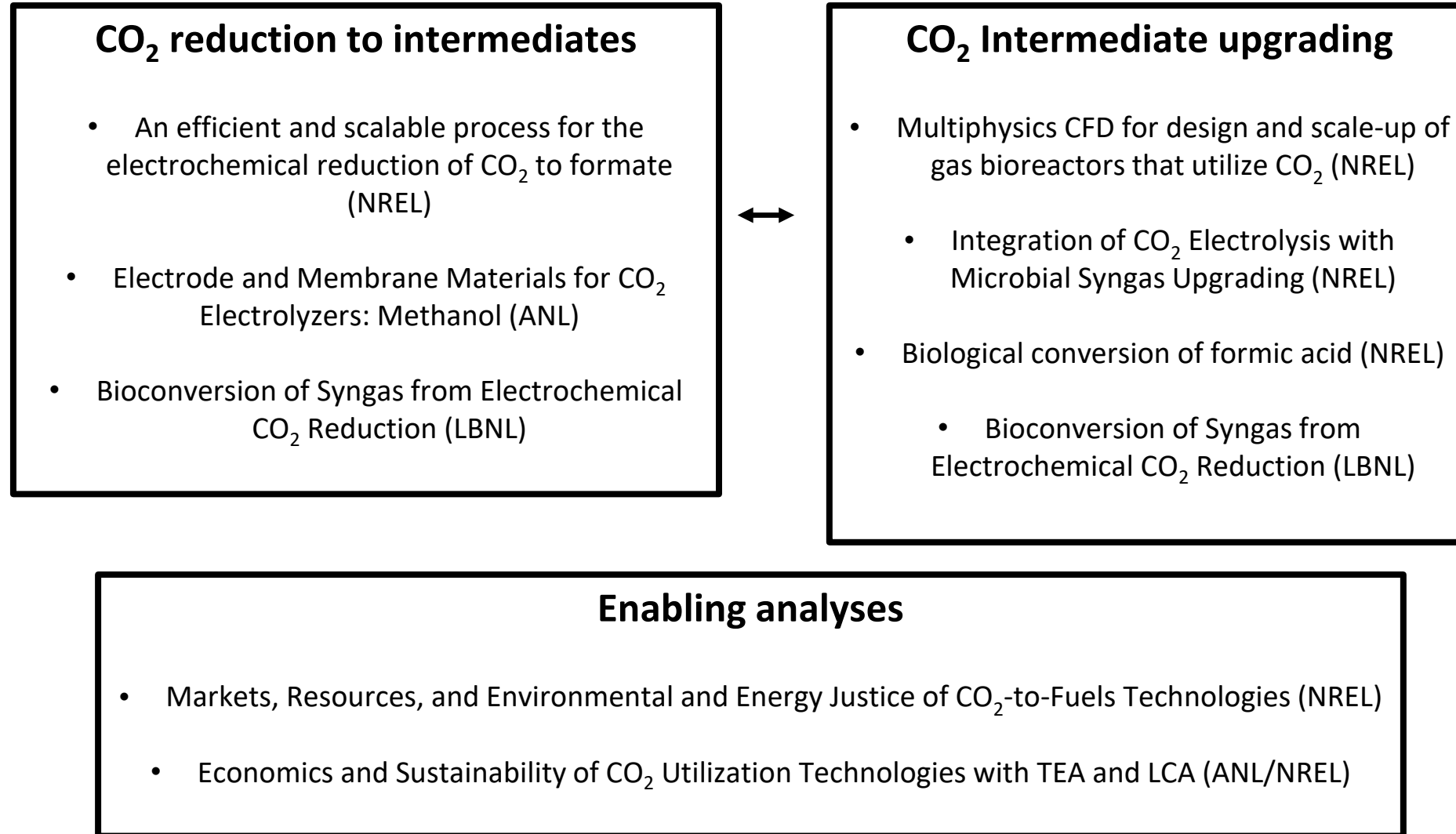


<https://www.electrochaea.com/about/>
<https://www.carbonrecycling.is/co2-methanol>

Secondary Conversion Pathways

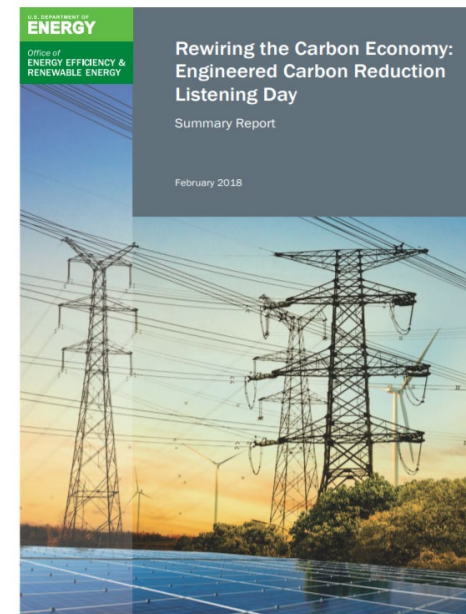


CO₂-to-Fuels Consortium Structure



CO₂ Utilization at BETO

- Interest in subject intensified in Early 2017
- Solicited for SBIR projects in CO₂U in Spring 2017
- Detail to the Office of Fossil Energy in March 2017
- Hosted the “Engineered Carbon Reduction Listening Day” in Summer 2017



CO₂ Utilization at BETO - Workshop

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 CO₂ reduction needs more work in redox/catalyst materials.

Highlights from the workshop:

1. There is a lot of uncertainty around what is/isn't possible in the field of CO₂ reduction. BETO is well equipped to address this given the existing catalysis experience at the labs.
2. Biological upgrading of reduced carbon intermediates is a space in which BETO excels and could be readily coupled to CO₂ utilization technologies.
3. These technologies are extremely well suited for biorefinery integration.

FY18 CO₂ Utilization at BETO

Started the “*Feasibility Study of Utilizing Electricity to Produce Intermediates from CO₂*” AOP at NREL (\$400k/yr). Also launched a biological CO₂ fermentation AOP.

Launched another round of SBIR topics on CO₂ Utilization

FY18: Released the BEEPS FOA, which ended up awarding \$4.5M to 3 “rewiring” projects which coupled carbon reduction to biological upgrading

Energy &
Environmental
Science



PERSPECTIVE

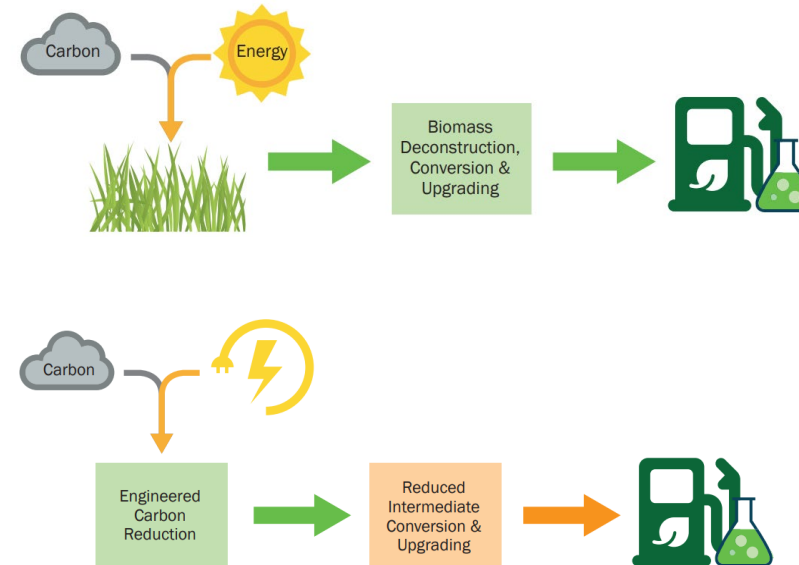
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2020, 13, 472

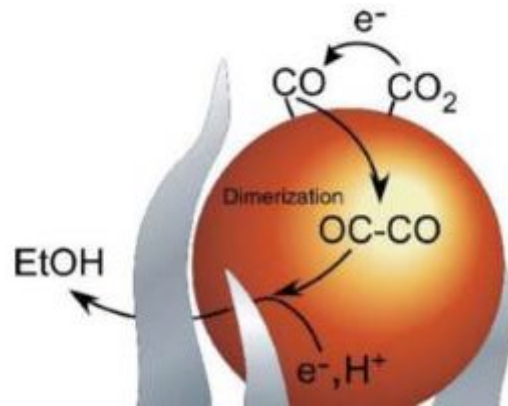
Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO₂ utilization†

R. Gary Grim, Zhe Huang, Michael T. Guarnieri, Jack R. Ferrell III, Ling Tao * and Joshua A. Schaidle *



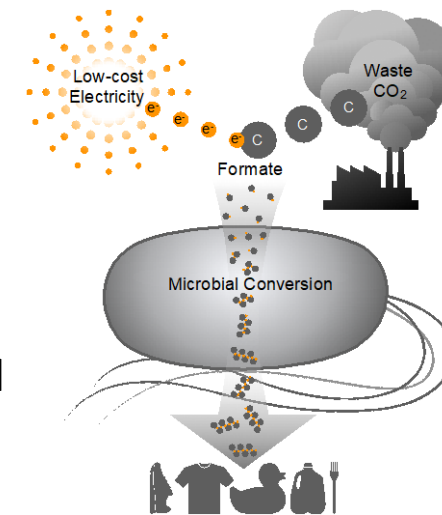
FY19 CO₂ Utilization at BETO

Biopower lab call funded CO₂ utilization efforts in biomethanation at NREL and LLNL as well as flue gas conversion to fuel (NREL/Dioxide Materials/Lanzatech)



Funded new ChemCatBio efforts on CO₂ electrocatalysis at ORNL and NREL

Lab call on C1 intermediate upgrading and awarded 3 projects for formate upgrading



FY20 CO₂ Utilization at BETO

Topic Area 7: Scalable CO₂ Electrocatalysis

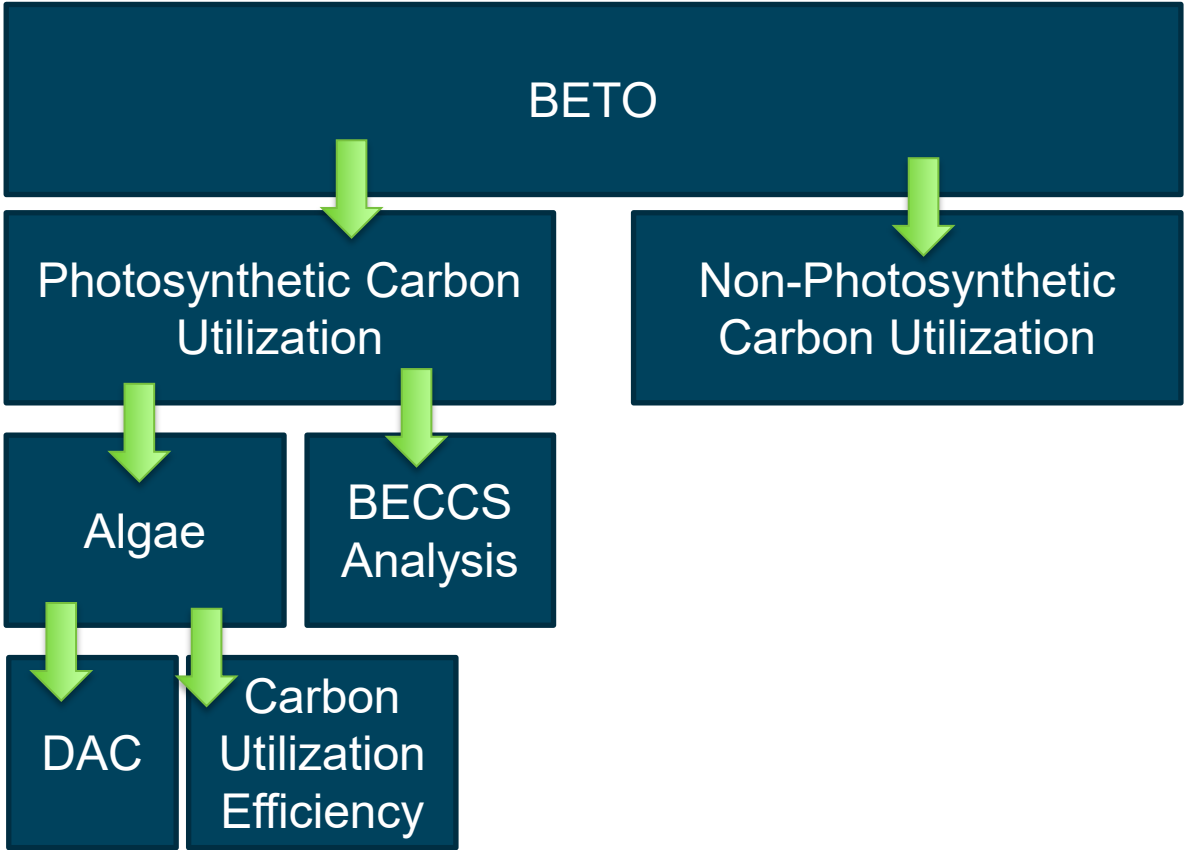
Sought efforts in electrocatalytically converting CO₂ to C1 or C2 intermediates and pushed the boundaries of what is possible in terms of scale, Faradaic efficiency, and current density. \$8M total, 3 projects

Collaborated with FCTO to fund NREL ESIF to work on directly integrating H₂ generation into a biomethanation reactor for increased energy efficiency and reduced capital intensity (\$600k BETO, \$100k FCTO)

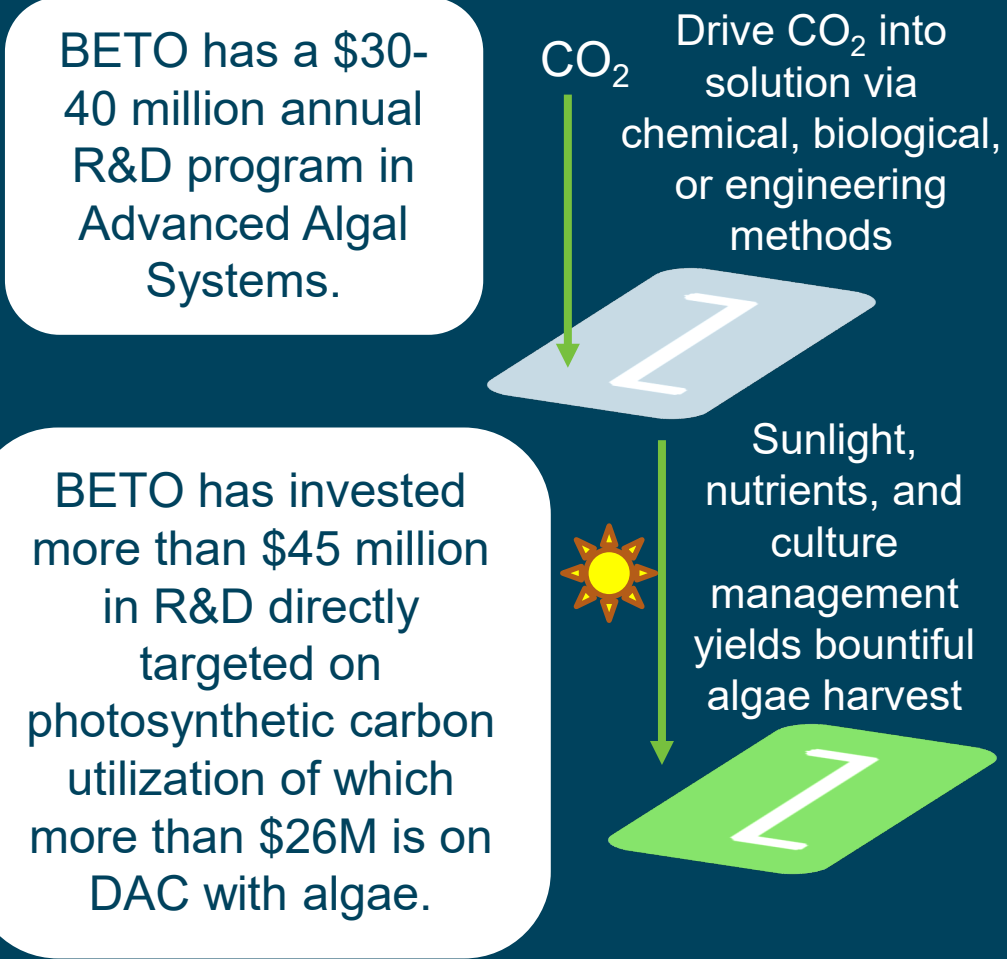


Set up the Net-Zero Tech Team analyses (\$400k)

BETO's Carbon Utilization Efforts



Innovative R&D keeps algae as a forefront technology for the bioeconomy and circular carbon economy.

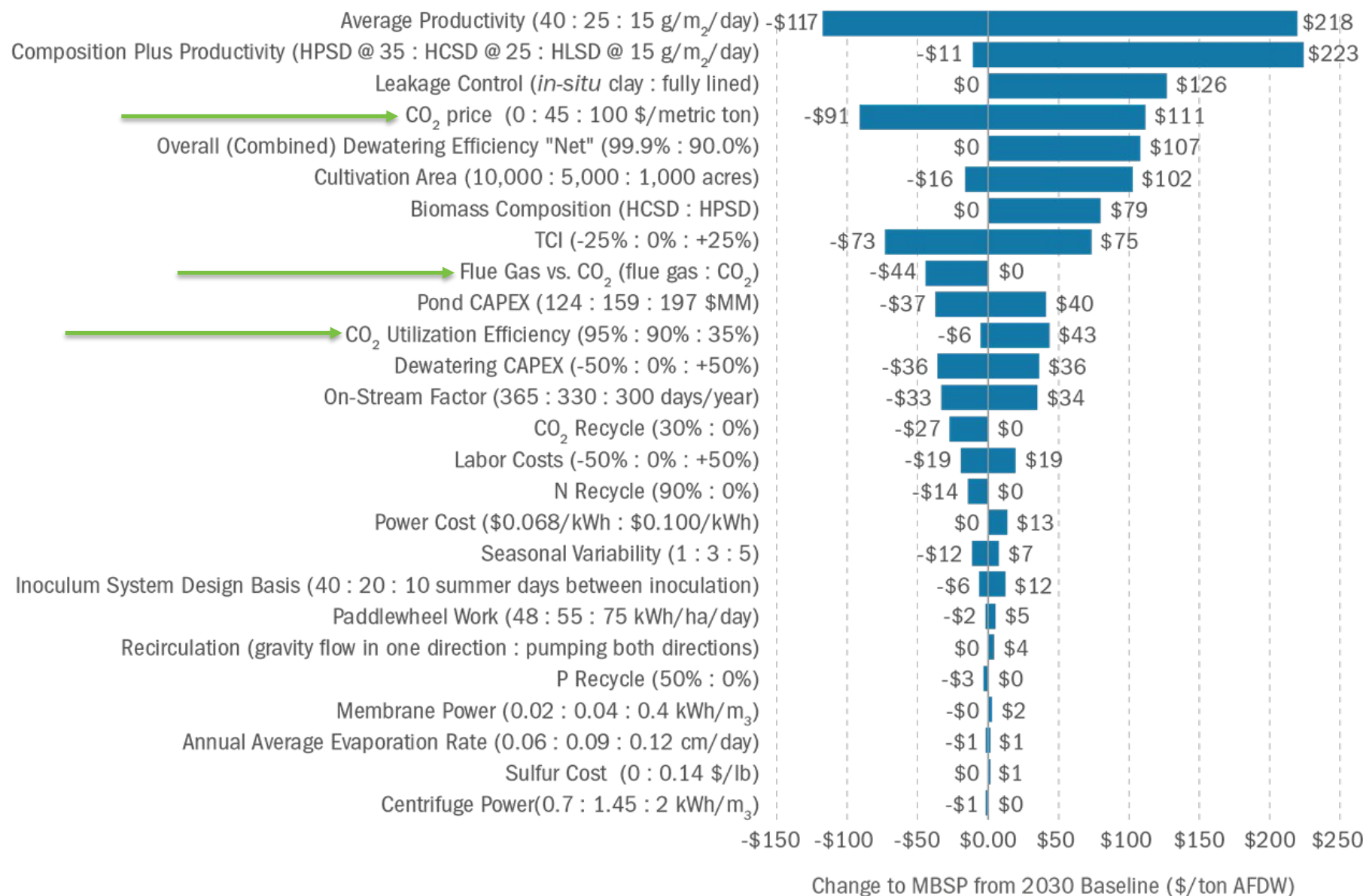


Algae – Perfect Biological, Photosynthetic Capture and Utilization Mechanism!!

- Initial CO₂-focused projects awarded from Targeted Algal Biofuels and Bioproducts FOA in 2015 (one on CO₂ from flue gas, one on direct air capture)
- Algae Cultivation for Carbon Capture and Utilization Workshop, May 23, 2017 (in coordination with Office of Fossil Energy and Stanton Energy Center)
- Efficient Carbon Utilization in Algal Systems FOA, 2018 (two topic areas – CO₂ utilization within cultivation systems and direct air capture)
- Coordination/Information Sharing with the Office of Fossil Energy (most recently coordinated language, metrics, topic areas for both FE's and BETO's FY20 FOAs, including participation on each other's FCBs; sharing project info for synergies and to avoid duplicative efforts)
- FY20 BETO Multi-topic FOA – Topic Area 3, Algal Bioproducts and CO₂ Direct Air Capture Efficiency (all projects include direct air capture technologies and CO₂ utilization metrics/goals)
- FY21 Feedstocks Technologies and Algae FOA – Topic Area 2, Algae Productivity Exceeding Expectations (APEX) (two subtopics, one on increasing productivity utilizing traditional carbon supplies and one on increasing productivity utilizing direct air capture)
- FY22 Carbon Utilization Technology: Improving Efficient Systems for Algae – (joint FOA with FECM) Topic Area 1, Carbon Utilization Efficiency from Biomass- or Atmospheric- Based Sources of Carbon Dioxide



CO₂ Capture and Utilization – Impact on Algae Costs

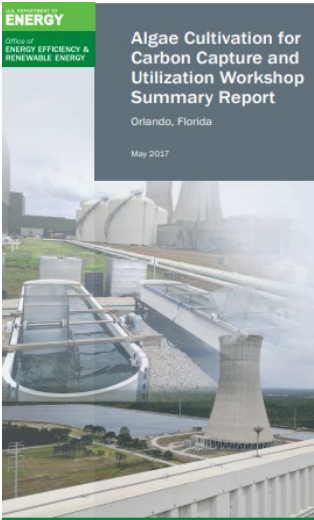


Algae – Early DAC and Flue Gas Capture Adopter

BETO has **partnered with the Office of Fossil Energy and Carbon Management (FECM)** on carbon utilization algae efforts to investigate both flue gas capture and direct air capture (DAC) to reduce delivered CO₂ costs and provide added value.

Selection of FOA awards that include carbon utilization from a point source and direct air capture

2015

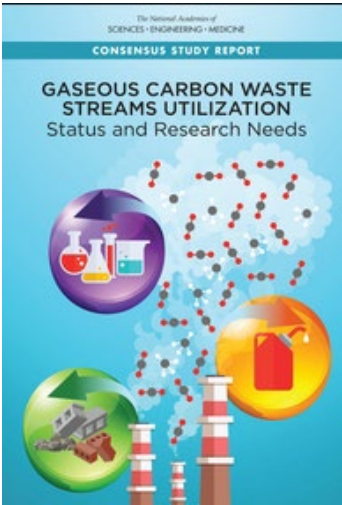


2017

ECUAS Topic language developed with input from FE

45Q includes algae as a CCU technology

2018



2017-2019

ABCDE Scoping on FOA discussed with FE
FE reviewer
FE Federal Consensus Board

The IRS released a new set of regulations for the Section 45Q tax code that can award a federal investment tax credit of up to \$35 per ton for carbon utilization with algae.

2020

Selection of APEX FOA awards that include increased productivity and carbon utilization from a point source or direct air capture

2021

Selection of Joint FOA awards that include increased carbon utilization, reduced costs, and reduced GHG emissions

2022

Enabling Technology for Algae Utilization of CO₂ from DAC

2018 BETO FOA

Engineering

Chemically

Biologically

Technology development approaches for enabling DAC used by FOA awardees

Direct Air Capture of CO₂ and Delivery to Photobioreactors for Algal Biofuel Production, \$2M

Air Carbon for Algae Production – AirCAP, \$2.2M

Enhanced Algal Production of CA for Improved Atmospheric Delivery of CO₂ to Ponds, \$2M

CO₂ concentration in air is about 405ppm. Oxygen in air is **about 500 times** higher than CO₂

Team: Georgia Tech, Global Thermostat, Algenol Biotech, NREL

Team: MicroBio Engineering Inc , PNNL, Qualitas Health, Global Thermostat

Team: J. Craig Venter Institute, Global Algae Innovations, Cal Poly San Luis Obispo

Use DAC machine with amine-based sorbents to capture CO₂ and deliver to algae cultivation systems

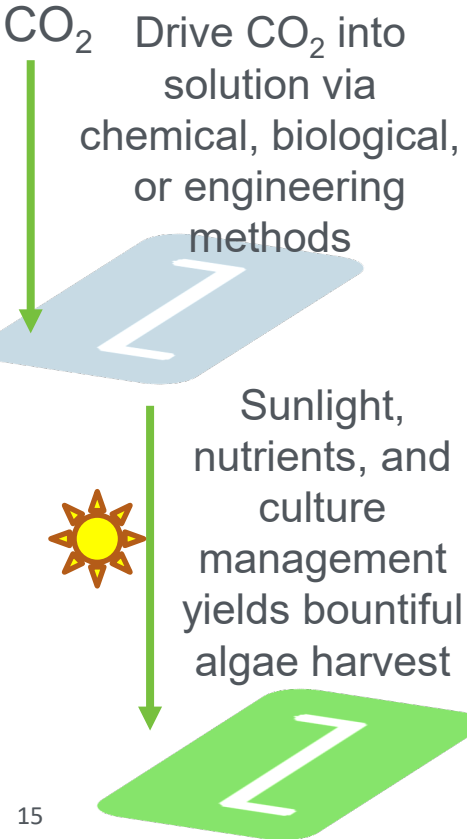
Use pH of the algae cultivation system to convert CO₂ into a more soluble species

Use a biologically produced enzyme to catalyze CO₂ into a more soluble species

This project will reduce algal biofuel costs and carbon intensity by using 20% or more of CO₂ from DAC and lower the cost CO₂ collection from air by developing DAC technology that utilizes improved sorbents and less intense operating conditions.

Direct mass-transfer of air-CO₂ into algal ponds is limited by diffusion of CO₂ at the air-water interface and the subsequent slow hydration of dissolved CO₂ into carbonic acid. This project will focus on accelerating transfer from air CO₂ into ponds at high pH, as well as biological and physical methods.

This project will utilize carbonic anhydrase (CA) to catalyze hydration of dissolved CO₂ to bicarbonate, thereby enhancing delivery of atmospheric CO₂ to the growth medium. Commercial CA use is cost-prohibitive at scale, therefore algal-derived extracellular CA production will be evaluated through the generation of transgenic lines.



TOPIC 3: Algae Bioproducts and CO₂ Direct Air Capture and Efficiency

The objective of Topic 3 was to lower the MFSP of algal biofuels through increased algae product value and/or yields. Utilization of direct air capture for the CO₂ source was a requirement.

Awardee	Title	Summary	Funding
Global Algae Innovations	Production of Algal Biofuel and Bioproducts with CO ₂ Direct Air Capture	Cultivate algae solely on CO ₂ from direct air capture	\$2,000,000
Montana State University	Transforming High pH/High Alkalinity Cultivation Through Beneficial Microbiomes and Improved Pond Design	Cultivate algae in high pH/high alkalinity environment with enhanced direct air capture to produce fuels and high value products	\$2,000,000
Arizona State University	ASU's Polymer-enhanced Cyanobacterial Bioproductivity (AUDACity)	Utilize ASU's novel DAC technology that integrates newly developed CO ₂ capture polymers to continuously and rapidly deliver inorganic carbon directly into the algae cultivation medium	\$1,999,051
University of California, San Diego	Biomolecular Films for Direct Air Capture of CO ₂	Establish carbon sequestering molecular films for enhanced atmospheric CO ₂ capture and increased productivity in open pond algae systems	\$2,000,000

FY20 Algae Awards

Awardee	Title	Summary	Funding
Lumen Bioscience Incorporated	Alkaline Carbon Capture and Expression – Streamlined Spirulina Cultivated in Air for Reliable Bioproducts, Oil, and Nutrition	Lessen Spirulina cultivation dependence on concentrated CO ₂ , increase its energy dense components, and develop strains with expression of heterologous protein byproducts	\$2,000,000
MicroBio Engineering, Incorporated	Microalgae Commodities Production with a Direct Air Capture Process	Utilization of CO ₂ from air to cultivate microalgae and produce biomass for higher value nutritional products in the near term and commodities in the longer term; 2 approaches – use of Global Thermostat’s direct air capture technology and use of the cultures and systems themselves to provide CO ₂ absorption from the air	\$1,999,882
Duke University	Development of High Value Bioproducts and Enhancement of Direct-Air-Capture Efficiency with a Marine Algae Biofuel Production System	Increase the market value of post-fuel algae biomass residues by assessing alternative high-value products and demonstrating direct air capture as the source of CO ₂	\$1,967,473

Algae Productivity Exceeding Expectations (APEX)
**Topic Area 2b: Improvements in Productivity with Direct Air Capture
from Ambient Air**

FY21 Algae Awards

Awardee	Title	Summary	Funding
Arizona State University	Direct Air Capture Integration with Algae Carbon Biocatalysis	Uncouple algae farming from point source CO ₂ by relying on novel DAC-sourced CO ₂ , and CO ₂ delivery innovations increases national deployment potential; metabolic engineering of Calvin Cycle control demonstrated in production strain translates broadly to improve photosynthetic carbon assimilation	\$3,200,000
University of Toledo	Minimizing Organic Carbon Losses to Improve Net Productivity in Direct Air Capture Cultivation	Demonstrate a >20% improvement of Fall and Spring season AFDW productivities over baseline values in outdoor raceway pond cultivations by employing novel alkaliphilic co-culture strategies.	\$3,200,000

FY22 Carbon Utilization Technology: Improving Efficient Systems for Algae

Topic Area 1: Carbon Utilization Efficiency from Biomass- or Atmospheric-Based Sources of Carbon Dioxide

FY22 Algae Awards

Awardee	Title	Summary	Funding
Colorado School of Mines	Efficient CO2 Use for Robust Marine Microalgae Biomass Yields	Increase the CO2 transfer and utilization efficiency of open algae raceway ponds using recently isolated marine alga in combination with innovation CO2 delivery mechanisms, pond designs, and operational strategies to achieve project objectives.	\$3,000,000
Colorado State University	Algal Turf Scrubbers: Improving Carbon Utilization and Productivity	Improve Algal Turf Scrubber (ATF) systems by increasing productivity so the system utilizes more CO2 from the atmosphere and produces biomass suitable for SAF precursor extraction or hydrothermal liquefaction (HTL) of the whole biomass.	\$2,998,499
Washington University in St. Louis	Enhancing Carbon Utilization by Algal Systems via Integrated Biogas Purification, Nitrogen Reuse, and Innovative Carbon Dioxide Delivery	Develop an innovative system to use anaerobic digester (AD) wastes to cultivate algae; use a novel reactor to recover nitrogen from AD effluent and generate an alkaline solution that is used to capture CO2 from biogas purification.	\$2,522,518

1 – Markets:

- Will this include anything about market acceptance for CO₂ derived from different sources? For example, particularly for the food and feed markets, is there or will there possibly be concern about where the CO₂ came from and what impurities/other constituents may be along for the ride?
- What specifications exist for CO₂ in various markets – purity, impurities/other constituents?
- Are there existing regulations regarding CO₂ for various products?
- How do these considerations impact the technical and financial viability of ‘waste’ CO₂ utilization?
- Maybe the overall consideration is that the market (avg. consumer) doesn’t know and doesn’t care – doesn’t need to know or care.

2 – Infrastructure: Seems like early studies on CO₂ capture and utilization from point sources was cost prohibitive if use was not co-located or at least close (less than 50 miles) to the collection point (too expensive to pipe/transport long distances). Is this still true? Is there a map or study possibly that overlays point sources with existing infrastructure (distances, etc.)? This could be useful in identifying where the infrastructure needs are (especially in rural areas where CO₂ utilization technologies may be – algae, etc.)

Thank you, questions?



Useful reports

[Federal Activities Report on the Bioeconomy: Algae](#)

[2019 BIOENERGY TECHNOLOGIES OFFICE 2019 R&D State of Technology](#)

[2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling](#)

[2016 National Algae Technology Review](#)

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