BETO efforts in carbon utilization

Ian Rowe

8 March 2021

Technology Manager

Bioenergy Technologies Office

Carbon Utilization

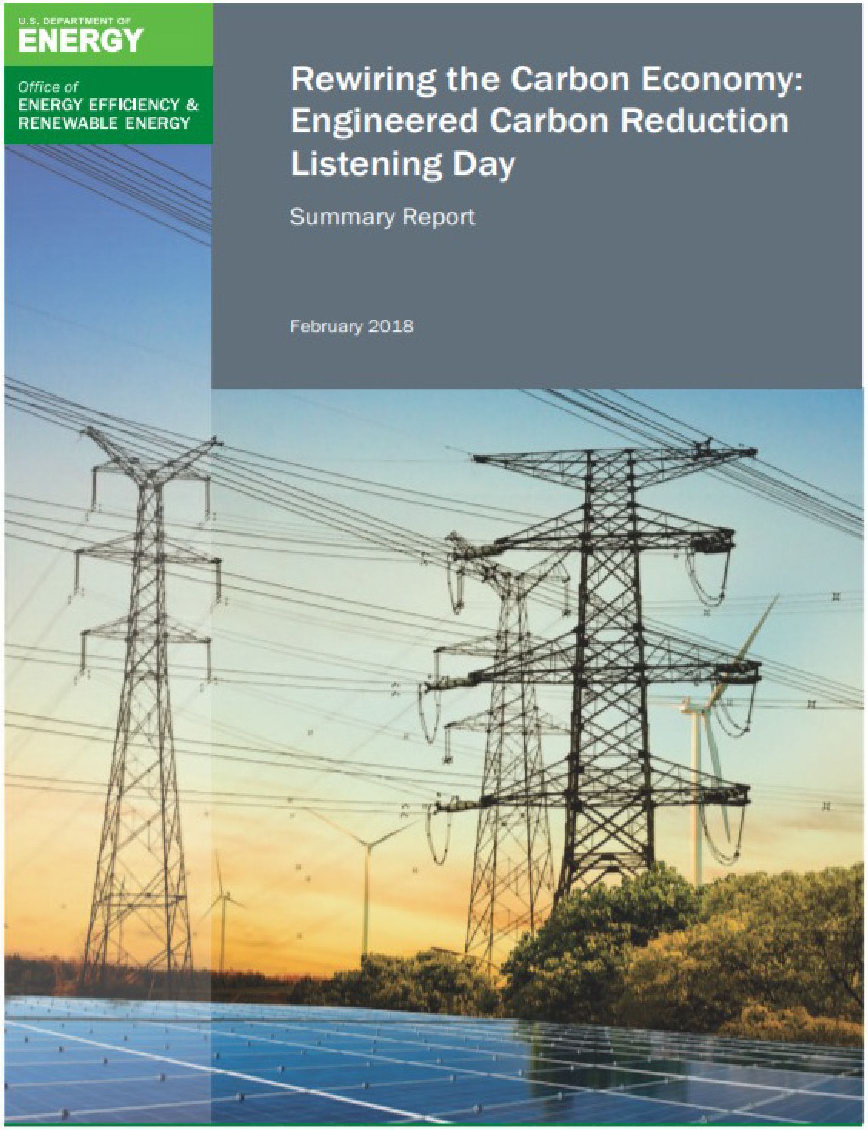





Everything BETO does is carbon utilization

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

2017 CO_2 Utilization workshop



U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Rewiring the Carbon Economy: Engineered Carbon Reduction Listening Day

Summary Report

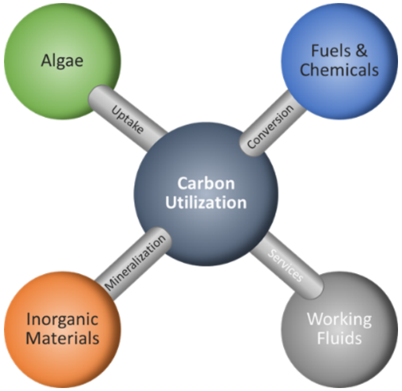
February 2018

Highlights from the workshop:

1. There is a lot of uncertainty around what is/isn't possible in the field of CO_2 reduction. BETO is well equipped to address this given the existing catalysis experience at the labs.
2. Upgrading of reduced carbon intermediates is a space in which BETO excels and could be readily coupled to CO_2 utilization technologies
3. These technologies are extremely well suited for biorefinery integration

Other CO_2 Utilization efforts

Algenol Biotech, LLC cultivates spirulina in photobioreactors at a facility in southwest Florida. *Photo from Algenol Biotech LLC.*



JCAP
JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS

NASA
CO_2 Conversion
Challenge

arpa·e
CHANGING WHAT'S POSSIBLE

- There is a lot of fantastic work being done on CO_2 utilization
- Significant barriers exist in getting these technologies beyond bench scale
- A “pathway-focused” applied R&D approach would be valuable

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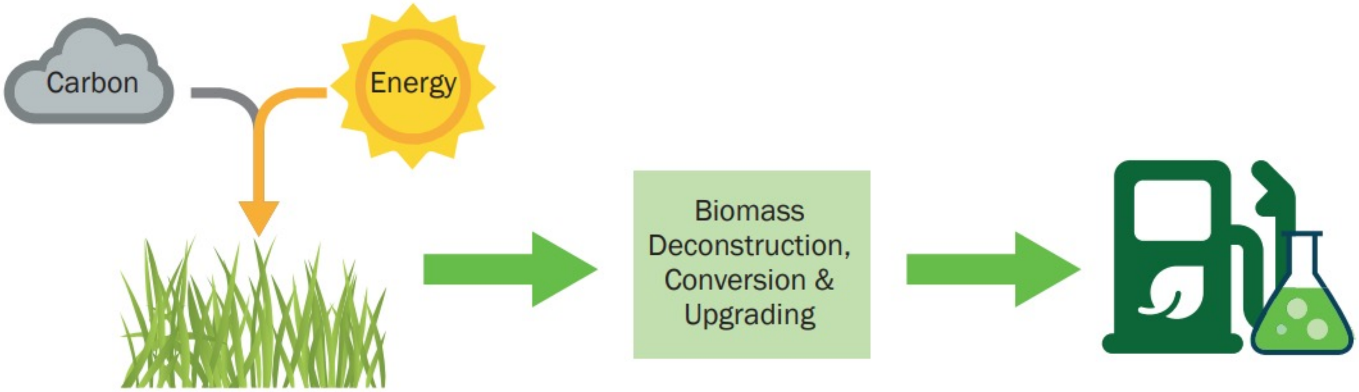
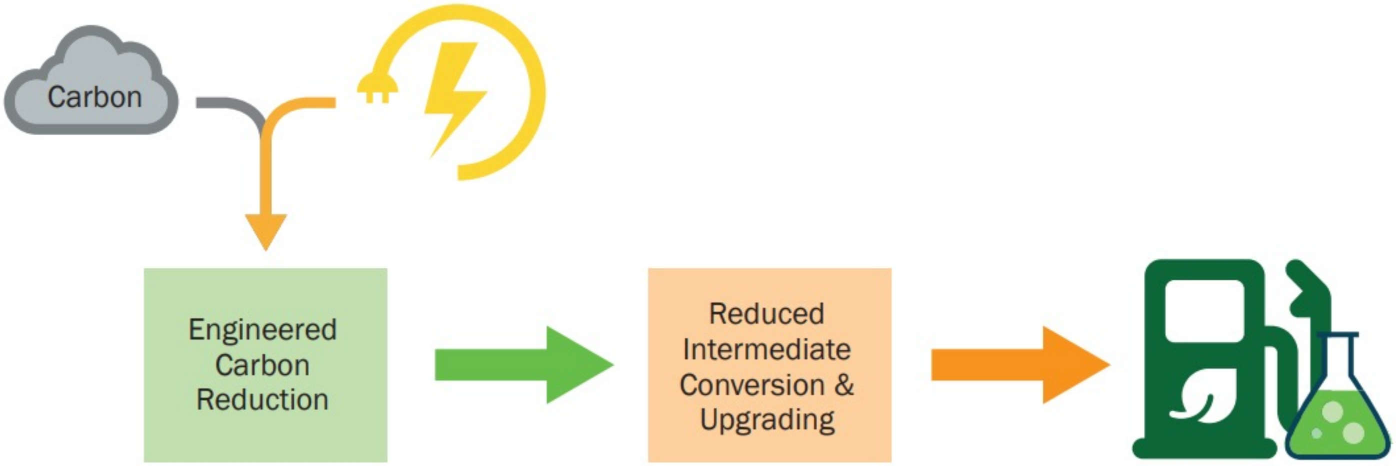
BETO Efforts in CO_2 Utilization



Carbon

Energy

Biomass Deconstruction, Conversion & Upgrading



Carbon

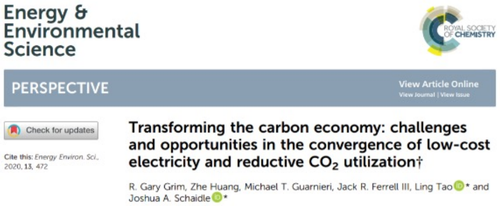
Engineered Carbon Reduction

Reduced Intermediate Conversion & Upgrading

FY18 CO_2 Utilization at BETO

Lab Projects:

- Started the "*Feasibility Study of Utilizing Electricity to Produce Intermediates from CO_2*" AOP. - NREL
- Electrocatalytic CO_2 Utilization AOP - NREL


Energy & Environmental Science

PERSPECTIVE

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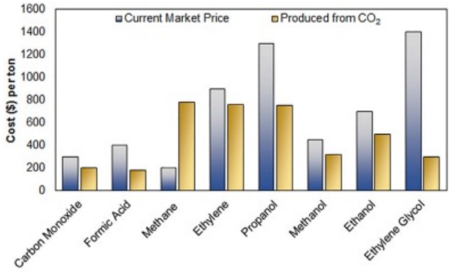
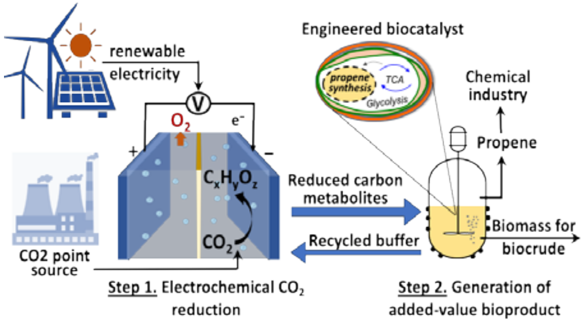
Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO_2 utilization†

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



BEEPS Rewiring FOA Topic Area:

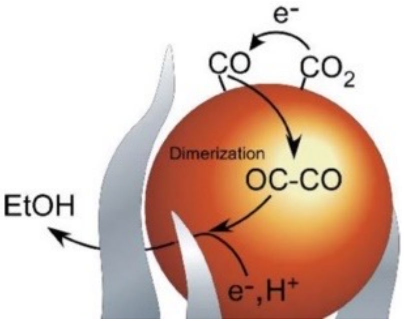
- *Electrocatalytic conversion of CO_2 to formic acid via microstructured materials* - Montana State University and University of Southern FL
- *Production of bioproducts from electrochemically-generated C1 intermediates* - Lanzatech and Dioxide Materials
- *Integrating Chemical Catalysis and Biological Conversion of Carbon Intermediates for Converting CO_2* - Johns Hopkins University and SDSU



FY19 CO_2 Utilization at BETO

Biopower lab call:

- *Biomethanation to Upgrade Biogas to Pipeline Grade Methane* – NREL
- *Modular Microbial Electromethanogenesis Flow Reactor for Biogas Upgrading* – LLNL
- *Integration of Flue Gas CO2 Electrolysis with Microbial Syngas Fermentation* - NREL



Seed lab call:

- *Hybrid electro- and thermo-catalytic upgrading of CO2 to fuels and C2+ chemicals* - ORNL

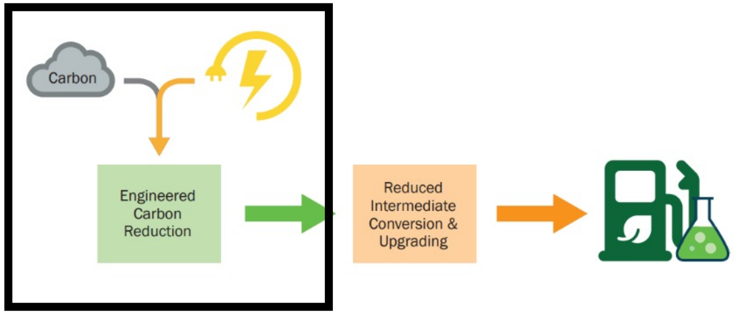
Formate lab call:

- *Improving formate upgrading by Cupriavidus necator* – NREL
- *Enhancing Acetogen Formate Utilization to Value-Added Products* - NREL
- *Synthetic C1 Condensation Cycle for Formate-Mediated ElectroSynthesis* – NREL/LBNL

FY20 CO_2 Utilization at BETO

Scalabe CO_2 Electrocatalysis **FOA Topic Area**:

- *Electrolyzers For CO_2 Conversion from BioSources*– Dioxide Materials
- *Electrochemical Production of Formic Acid from Carbon Dioxide in Solid Electrolytes*– University of Delaware
- *PEM CO_2 Electrolyzer Scaleup to enable MW-Scale Electrochemical Modules*- Opus 12



Collaborated with HFTO to fund to work on directly integrating H_2 generation into a biomethanation reactor for increased energy efficiency and reduced capital intensity

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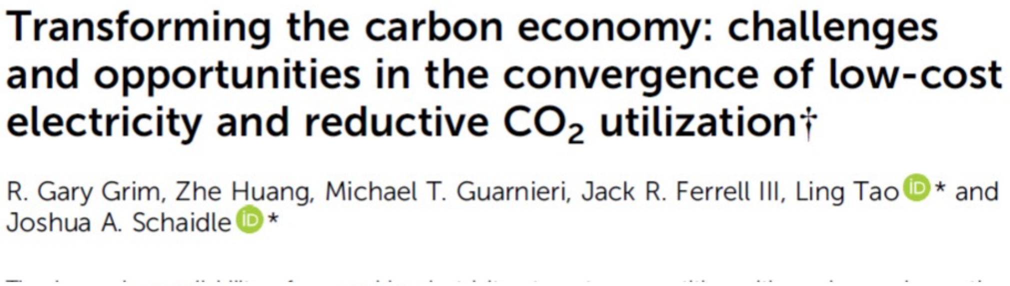
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Set up the Net-Zero Tech Team analyses

- Includes TEA/LCA examination of CO_2-to-fuels

CO_2 Utilization



Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO_2 utilization†

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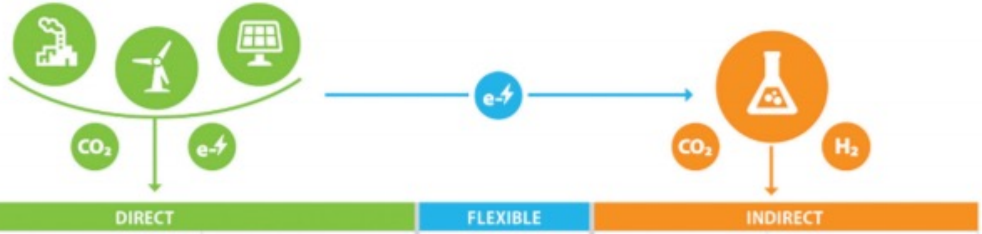
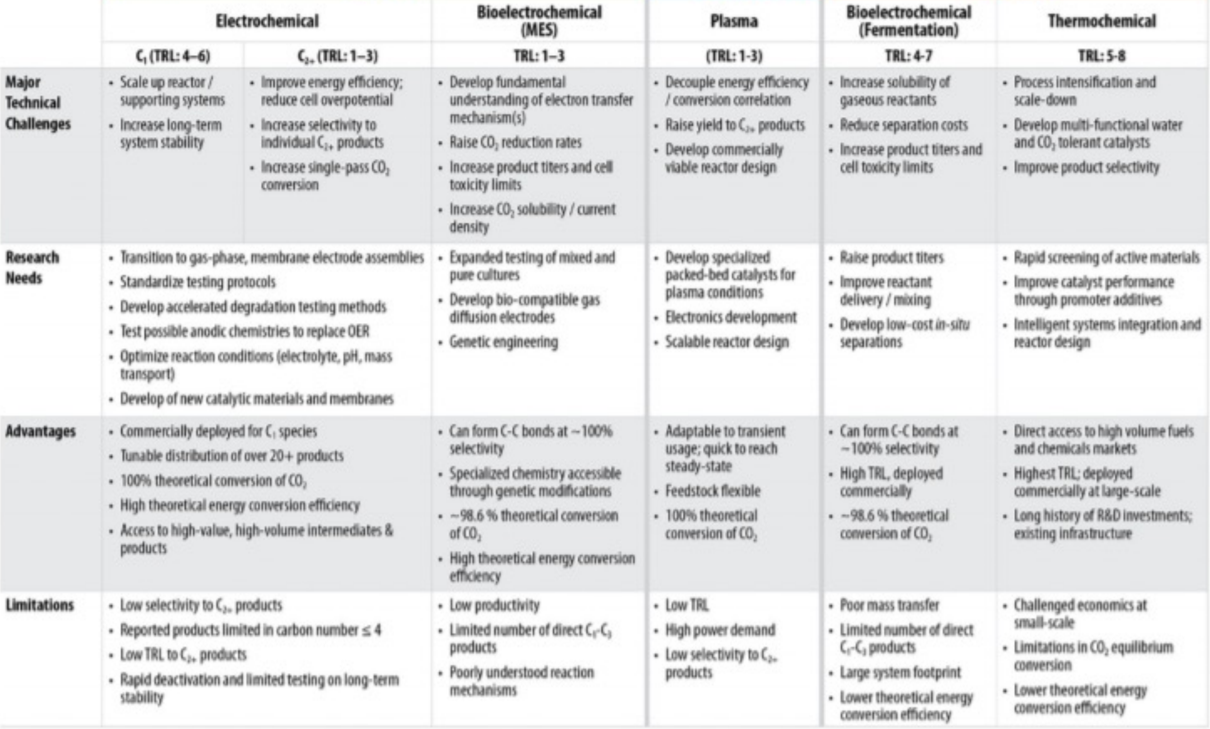
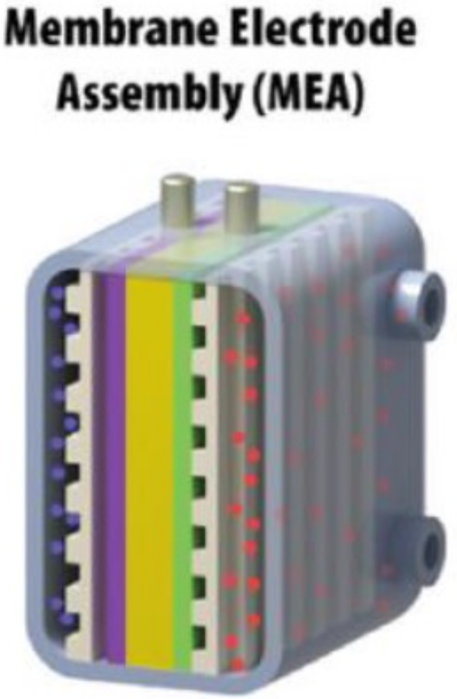




	DIRECT			FLEXIBLE	INDIRECT	
	Electrochemical		Bioelectrochemical (MES)	Plasma	Bioelectrochemical (Fermentation)	Thermochemical
	C_1 (TRL: 4–6)	C_{2+} (TRL: 1–3)	TRL: 1–3	(TRL: 1-3)	TRL: 4-7	TRL: 5-8
Major Technical Challenges	• Scale up reactor / supporting systems • Increase long-term system stability	• Improve energy efficiency; reduce cell overpotential • Increase selectivity to individual C_{2+} products • Increase single-pass CO_2 conversion	• Develop fundamental understanding of electron transfer mechanism(s) • Raise CO_2 reduction rates • Increase product titers and cell toxicity limits • Increase CO_2 solubility / current density	• Decouple energy efficiency / conversion correlation • Raise yield to C_{2+} products • Develop commercially viable reactor design	• Increase solubility of gaseous reactants • Reduce separation costs • Increase product titers and cell toxicity limits	• Process intensification and scale-down • Develop multi-functional water and CO_2 tolerant catalysts • Improve product selectivity
Research Needs	• Transition to gas-phase, membrane electrode assemblies • Standardize testing protocols • Develop accelerated degradation testing methods • Test possible anodic chemistries to replace OER • Optimize reaction conditions (electrolyte, pH, mass transport) • Develop of new catalytic materials and membranes		• Expanded testing of mixed and pure cultures • Develop bio-compatible gas diffusion electrodes • Genetic engineering	• Develop specialized packed-bed catalysts for plasma conditions • Electronics development • Scalable reactor design	• Raise product titers • Improve reactant delivery / mixing • Develop low-cost *in-situ* separations	• Rapid screening of active materials • Improve catalyst performance through promoter additives • Intelligent systems integration and reactor design
Advantages	• Commercially deployed for C_1 species • Tunable distribution of over 20+ products • 100% theoretical conversion of CO_2 • High theoretical energy conversion efficiency • Access to high-value, high-volume intermediates & products		• Can form C-C bonds at ~100% selectivity • Specialized chemistry accessible through genetic modifications • ~98.6 % theoretical conversion of CO_2 • High theoretical energy conversion efficiency	• Adaptable to transient usage; quick to reach steady-state • Feedstock flexible • 100% theoretical conversion of CO_2	• Can form C-C bonds at ~100% selectivity • High TRL, deployed commercially • ~98.6 % theoretical conversion of CO_2	• Direct access to high volume fuels and chemicals markets • Highest TRL; deployed commercially at large-scale • Long history of R&D investments; existing infrastructure
Limitations	• Low selectivity to C_{2+} products • Reported products limited in carbon number ≤ 4 • Low TRL to C_{2+} products • Rapid deactivation and limited testing on long-term stability		• Low productivity • Limited number of direct C_1-C_3 products • Poorly understood reaction mechanisms	• Low TRL • High power demand • Low selectivity to C_{2+} products	• Poor mass transfer • Limited number of direct C_1-C_3 products • Large system footprint • Lower theoretical energy conversion efficiency	• Challenged economics at small-scale • Limitations in CO_2 equilibrium conversion • Lower theoretical energy conversion efficiency

CO_2 Utilization



Understanding and diagnosing the state of AEM and PEM CO_2 electrolyzers

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CO_2 Utilization

Dioxide Materials™
The CO_2 Recycling Company™

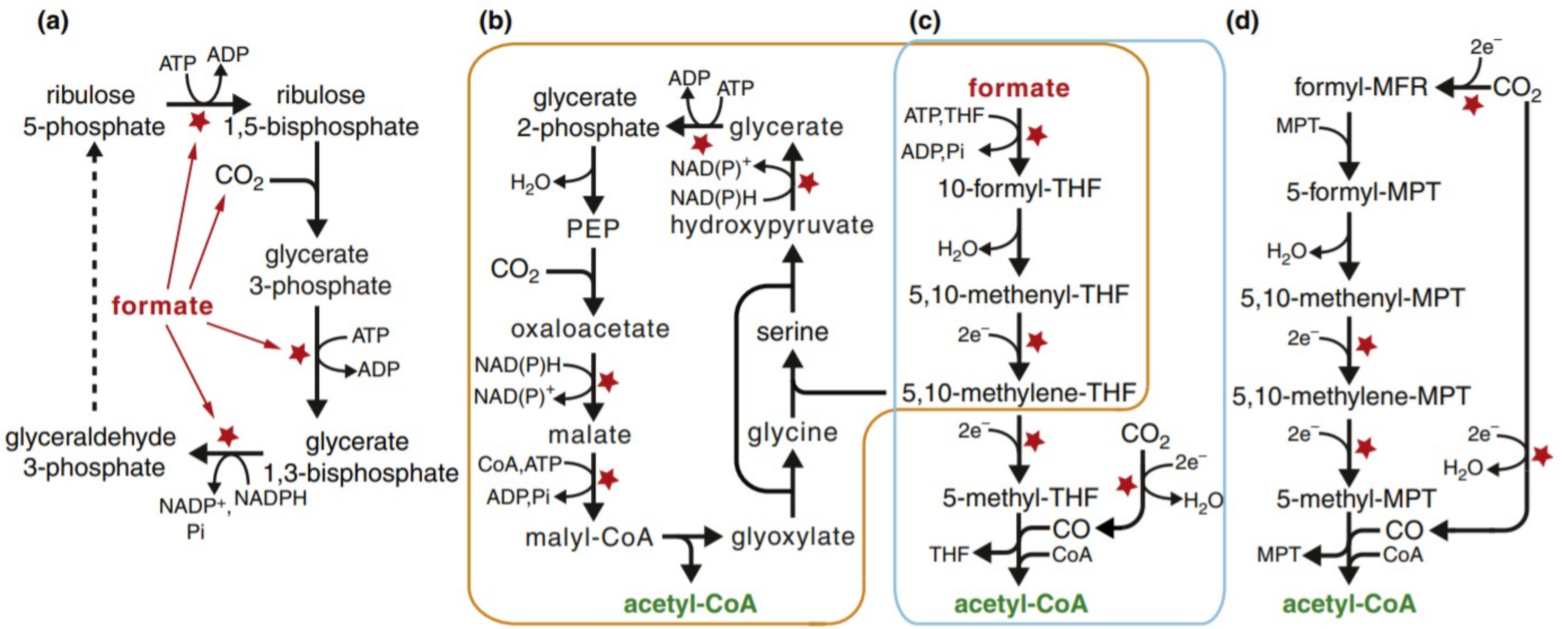
opus 12

University of Delaware®

Scaling up PEM, AEM and solid-state electrolyte CO_2 electrolyzers to:

- 750cm^2 active surface area
- 200mA/cm^2
- 90% FE
- 1000 hr run time

CO_2 Utilization

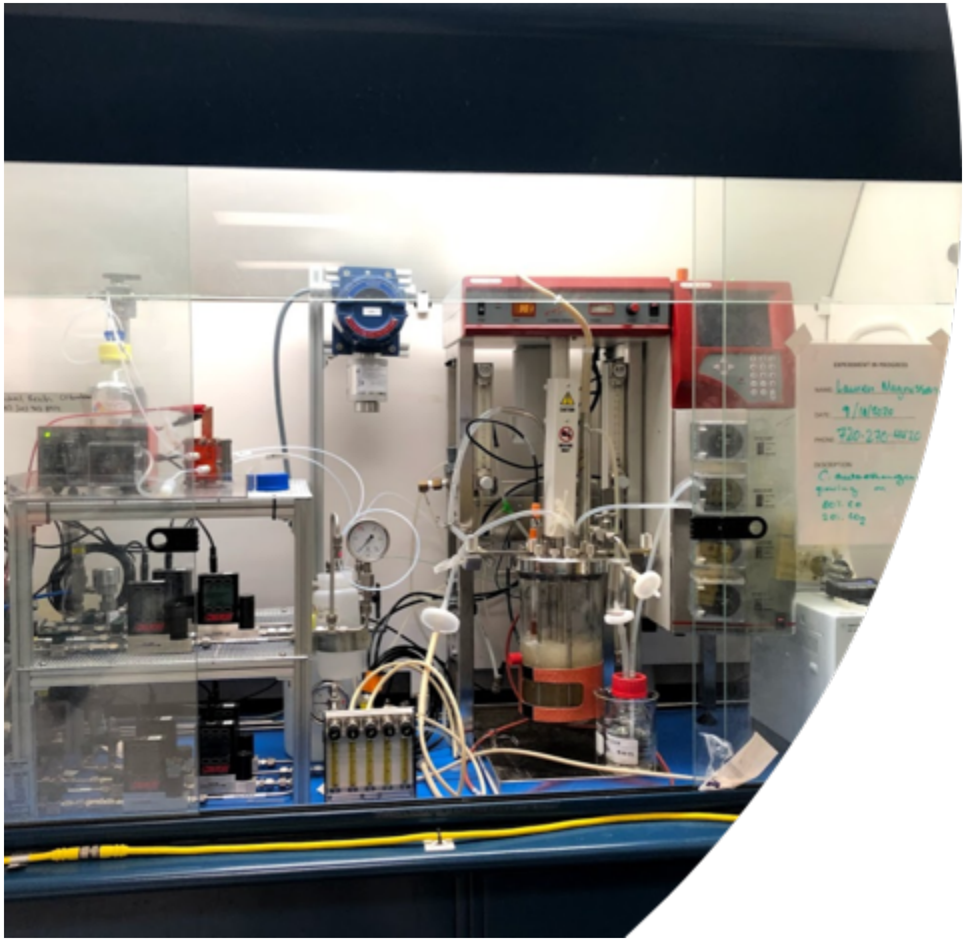


Bar-Even et al., 2016

Current Opinion in Chemical Biology

Engineering microorganisms to consume C1 intermediates and generate products

CO_2 Utilization



LanzaTech

Dioxide Materials
The CO_2 Recycling Company™

San Diego State University

Johns Hopkins University

Montana State University

Developing integrated CO_2 utilization capabilities.

CO_2 Utilization

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VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Explores several options for achieving Net-Zero Carbon fuels, notably *corn ethanol with CCS* as well as *CO_2 conversion to ethanol*.

Net-Zero Carbon Fuels: Renewable fuels made from some carbon feedstock that have a net life-cycle of zero

E-fuels: Synthetic fuels made from combining CO_2 and electricity/hydrogen

E-fuels CAN be net-zero carbon, but they are not inherently so and are not necessarily the easiest way to achieve low carbon intensity fuels

Broader opportunities in Carbon Management

Microsoft will be carbon negative by 2030

Jan 16, 2020 | Brad Smith - President

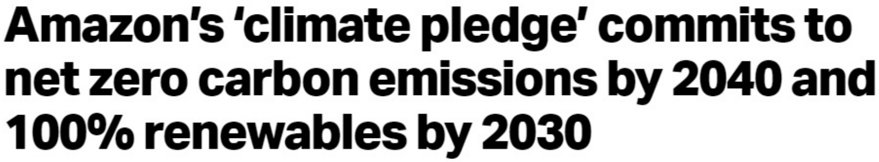
Sep 30, 2020, 10:01am EDT | 1,409 views

Walmart Pledges Zero Emissions By 2040

Coca-Cola targets net zero emissions by 2040 in Europe

By Rachel Arthur

07-Dec-2020 - Last updated on 07-Dec-2020 at 10:37 GMT



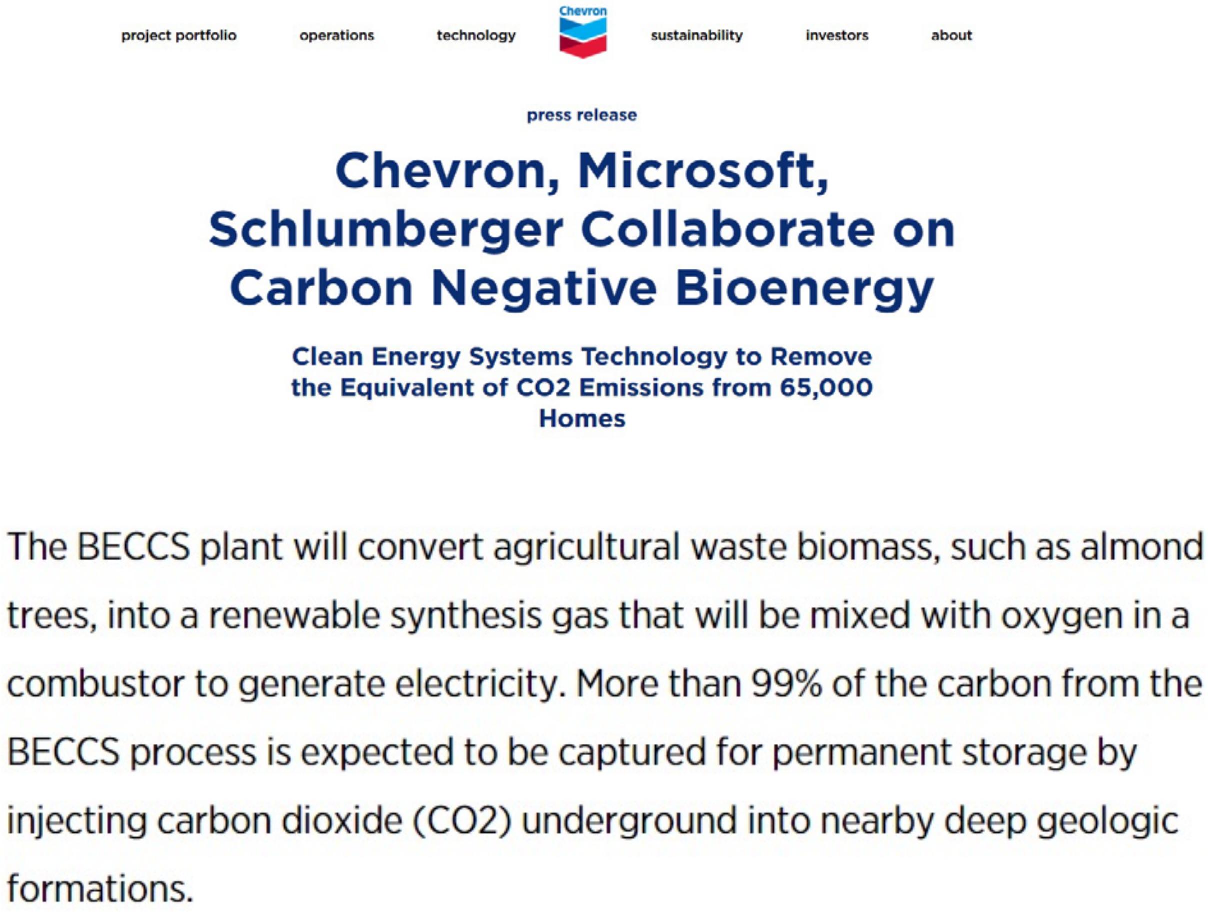
Amazon's 'climate pledge' commits to net zero carbon emissions by 2040 and 100% renewables by 2030

13 major airlines commit to joint 2050 net-zero vision

14 September 2020, source edie newsroom

There will be a growing demand to provide carbon management and drawdown as a service. DOE has the right set of tools to address the needs of this emerging market.

Broader opportunities in Carbon Management



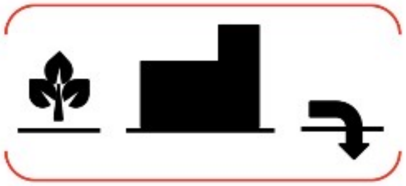
press release

Chevron, Microsoft, Schlumberger Collaborate on Carbon Negative Bioenergy

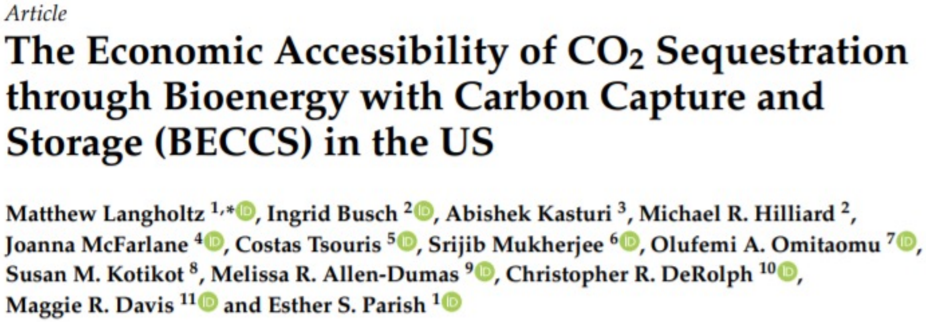
Clean Energy Systems Technology to Remove the Equivalent of CO2 Emissions from 65,000 Homes

The BECCS plant will convert agricultural waste biomass, such as almond trees, into a renewable synthesis gas that will be mixed with oxygen in a combustor to generate electricity. More than 99% of the carbon from the BECCS process is expected to be captured for permanent storage by injecting carbon dioxide (CO2) underground into nearby deep geologic formations.

Broader opportunities in Carbon Management



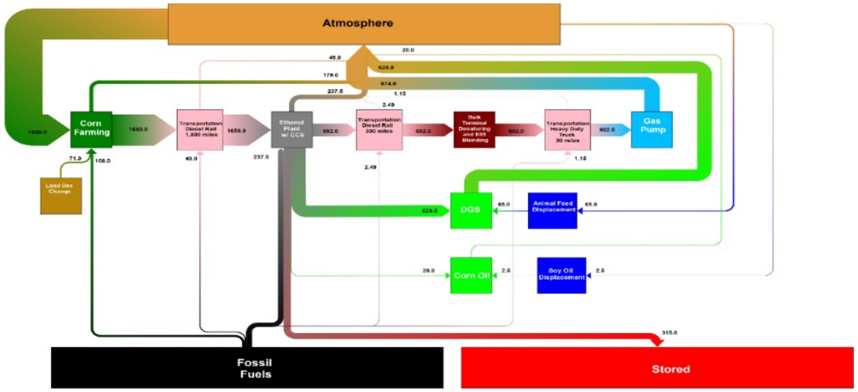
BECCS



Article

The Economic Accessibility of CO$_2$ Sequestration through Bioenergy with Carbon Capture and Storage (BECCS) in the US

Matthew Langholtz [1,*], Ingrid Busch [2], Abishek Kasturi [3], Michael R. Hilliard [2], Joanna McFarlane [4], Costas Tsouris [5], Srijib Mukherjee [6], Olufemi A. Omitaomu [7], Susan M. Kotikot [8], Melissa R. Allen-Dumas [9], Christopher R. DeRolph [10], Maggie R. Davis [11] and Esther S. Parish [1]



Assessing the potential for multiple bioproducts to drawdown and store carbon

Contact

Ian Rowe, Ph.D.

Technology Manager | Bioenergy Technologies Office
U.S. Department of Energy
o. 202-586-7720 | Ian.Rowe@ee.doe.gov