Rewiring Carbon Reduction

The Carbon Reduction and Valorization Initiative: A look into new cooperative efforts between The Office Of Fossil Energy and Bioenergy Technologies Office

Ian Rowe
Technology Manager
Office of Fossil Energy and Bioenergy Technologies Office
U.S. Department of Energy
What I wont be addressing:

Coal and Coal-Biomass-to-Liquids Program

- Convert coal to liquid fuels with biomass to reduce CO₂ emissions
- Mostly gasification/Fischer-Tropsch
- Slated to end under FY18 budget

DE-FOA-0001622: Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants.
- **Michigan State**: CAP for a novel CO₂ capture solution and polyurethane composites ($1.25M)
- **Uni of Illinois**: PBR algal growth with dewatering membrane development ($1.25M)
Lifecycle of traditional carbon sources in the bioeconomy

As we expand the bioeconomy, we put pressure on the land sector.
Renewable carbon bioeconomy puts pressure on the land sector

- What if we could avoid land use, simplify deconstruction and upgrading, reduce CO2 emissions, and increase energy security by rewiring the carbon cycle to produce our renewable carbon?
There is no shortage of CO2 feedstock, thanks to climate change!
9 large scale CCS units in operation in the US
- 4 Natural gas processing units
- 2 Fertilizer producers
- 1 SMR for H2 production
- 1 Ethanol facility
- 1 Power generating facility
- 22M ton/yr sequestered
- Only ADM is sequestered, the rest are EOR

Carbon capture unit flow diagram

Shute Creek, WY (7 Mtpa)

ADM, IL (1 Mtpa)
Petra Nova, TX (1.4 Mtpa). Only EGU CCS facility

Carbon Capture and Sequestration in the power sector

- CCS is a great tool, demonstrated to work
- Too expensive
- Needs enabling technology
Renewable Energy Deployment is picking up

May 2017 Total US Solar + Wind Generation: ~10% (EIA)
ELECTROFUELS: utilizing renewable electricity to make biofuels

- Funding: $50M from 6/2010 thru 12/2014
- Non-photosynthetic microbes transform CO$_2$ into fuels while using electricity to provide the energy needed to reduce carbon.

**Autotrophs:**
Convert light energy to chemical energy to make ATP. ATP provides the energy to reduce CO$_2$ to glucose:

$$6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$$

**Chemolithoautotrophs:**
Use inorganic sources (H$_2$, NH$_3$, S, Fe$^{+2}$) to generate ATP and reduce carbon

**Heterotrophs:**
Consume reduced carbon generated by autotrophs in cellular respiration to produce ATP:

$$\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$$

![Diagram of the process](attachment:image.png)
ELECTROFUELS: Renewable H2 as the source of reductant

7 Projects, totaling $23.8M

<table>
<thead>
<tr>
<th>Project</th>
<th>Awardee</th>
<th>$, M</th>
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</thead>
<tbody>
<tr>
<td>Engineering R. eutropha for Production of Isobutanol (IBT) Motor Fuel from CO2, H and O2</td>
<td>MIT</td>
<td>1.8</td>
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<tr>
<td>Bioprocess and Microbe Engineering for Total Carbon Utilization in Biofuel Production</td>
<td>MIT</td>
<td>3.9</td>
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<tr>
<td>Integrated Microbial Electrocatalytic (MEC) System for Liquid Biofuel Production from CO2</td>
<td>LBNL</td>
<td>3.4</td>
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<tr>
<td>H2-Dependent Conversion of CO2 to Liquid Electrofuels by Extremely Thermophilic Archaea</td>
<td>NC State</td>
<td>3.1</td>
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<tr>
<td>Bioconversion of Carbon Dioxide to Biofuels by Facultatively Autotrophic Hydrogen Bacteria</td>
<td>OSU</td>
<td>4</td>
</tr>
<tr>
<td>Novel Biological Conversion of Hydrogen and Carbon Dioxide Directly into Free Fatty Acids</td>
<td>OPX</td>
<td>6</td>
</tr>
<tr>
<td>Development of Rhodobacter as a Versatile Platform for Fuels Production</td>
<td>PSU</td>
<td>1.6</td>
</tr>
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ELECTROFUELS: Renewable H2 as the source of reductant

Penn State: Development of Rhodobacter as a Versatile Platform for Fuel Production

Genetic engineering of *Rhodobacter capsulatus*, a chemolithoautotroph, to use H2 to reduce CO2 and create a triterpene hydrocarbon fuel

- Poor productivity
- Difficult genetic manipulation
- Complicated fuel
## ELECTROFUELS: Using electricity more directly

4 Projects, totaling $14M

<table>
<thead>
<tr>
<th>Project</th>
<th>Awardee</th>
<th>$$, M</th>
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<tr>
<td>Electrofuels Via Direct Electron Transfer from Electrodes to Microbes</td>
<td>Umass Amherst</td>
<td>5.6</td>
</tr>
<tr>
<td>Engineering a Bacterial Reverse Fuel Cell</td>
<td>Harvard</td>
<td>4.2</td>
</tr>
<tr>
<td>Electroalcoholgenesis: Bioelectrochemical Reduction of CO2 to Butanol</td>
<td>MUSC</td>
<td>2.7</td>
</tr>
<tr>
<td>Biofuels from CO2 Using Ammonia or Iron-Oxidizing Bacteria in Reverse Microbial Fuel Cells</td>
<td>Columbia U.</td>
<td>1.5</td>
</tr>
</tbody>
</table>
ELECTROFUELS: Using electricity more directly

Umass Amherst: Electrofuels via Direct Electron Transfer from Electrodes to Microbes ($5.6M)

- acetogenic Clostridium
- Form bio-films on electrodes
- Organism directly uses electrons to power the CO2 reduction
Columbia: Biofuels from CO2 Using NH3 Oxidizing Bacteria in Reverse Microbial Fuel Cells ($1.5M)

ELECTROFUELS: Using electricity more directly

N. europaea, a chemolithoautotroph which can use ammonia (NH3) as a reducing agent, was used as the biocatalyst. Two reactors: One where electricity is used to regenerate NH3 as the reductant. The NH3 is then fed to the biocatalyst, along with CO2.
## ELECTROFUELS: reducing carbon via electricity

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<tr>
<td>Engineering E. coli as an Electrofuels Chassis for Isooctane Production</td>
<td>Ginkgo Bioworks</td>
<td>6.7</td>
</tr>
<tr>
<td>Electro-Autotrophic Synthesis of Higher Alcohols</td>
<td>UCLA</td>
<td>4.2</td>
</tr>
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</table>
ELECTROFUELS: reducing carbon via electricity

UCLA: Electro-Autotrophic Synthesis of Higher Alcohols ($4.2M)

- engineered *Ralstonia eutropha* to produce isobutanol from formic acid, which was generated by the reduction of CO2 at the cathode.

- In a simple setup of just formic acid fed into a fermenter, they were able to get butanol produced at 1.4 g/L

- With the electrochemical setup at left, they achieved 0.14 g/L butanol
Using the specific expertise in FE for CO2 utilization

Efficient Electrochemical CO₂ Conversion Powered by Renewable Energy

Degraff R. K., Kazimierczuk, Jay Thakkar, Rajan Siva, Christopher Matranga, Paul R. Olszynski, Chenjie Zeng, and Rongzhao Jin

National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, Pennsylvania 15234, United States

Department of Chemistry, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States

Supporting Information

Abstract: The catalytic conversion of CO₂ into industrially relevant chemicals is one strategy for mitigating greenhouse gas emissions. Among these, electrochemical CO₂ conversion technologies are attractive because they can operate with high reaction rates at ambient conditions. However,

DE-FOA-0001622: Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants ($5M)

Uni of Delaware: Electrochemical Conversion of Carbon Dioxide to Alcohols

GTI: High Energy Systems for Transforming CO₂ to Valuable Products

GTI: Nano-Catalyst on Ceramic Fibers for the Utilization of CO₂ to Produce Syngas

TDA Research: A New Process for CO₂ Conversion to Fuel via thermocatalysis

Southern Research: Nano-Engineered Catalyst for Olefin Production from Flue Gas

RTI: Novel Catalytic Process Technology for Utilization of CO₂ for Ethylene Oxide and Propylene Oxide Production
BETO has a vast portfolio of bioengineering expertise
Current electrocatalytic and biological technologies available
Rewiring carbon reduction to enable grid reliability and energy storage
## Early progress in the Carbon Reduction and Valorization Initiative

- Targeted funding opportunity for non-photosynthetic carbon reduction
  - *Biofuel and Bioproduct Precursors from Gaseous Waste Streams*

<table>
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<th>Non-photosynthetic carbon reduction</th>
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<tr>
<td>Opus 12 Incorporated</td>
<td>Utilization of waste CO$_2$ to make renewable chemicals and fuels</td>
</tr>
<tr>
<td>Reactive Innovations, LLC</td>
<td>Novel Cold Plasma System for the Reaction of CO$_2$ and Liquid Feed Streams for the Production of Value Added Products</td>
</tr>
<tr>
<td>Sustainable Innovations, LLC</td>
<td>Renewables-Driven Production of Organic Acids from Industrial CO$_2$ Waste Streams</td>
</tr>
<tr>
<td>Visolis, Inc</td>
<td>Production of High Value Products from Gaseous Waste Streams</td>
</tr>
</tbody>
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Early progress in the Carbon Reduction and Valorization Initiative

- New funding opportunity announcement. Out now!
  - Engineered Systems for Innovative Wet and Gaseous Waste Valorization
    - Topic B – Non-photosyntetic Carbon Dioxide Reduction and Biological Upgrading

CO2 Reduction Listening Day
July 7, 2017
International Solar Fuels Conference 2
La Jolla, CA
Congress likes the idea

**House:** “The Committee is aware of the significant benefits from the further development of electrochemical conversion of CO2 to syngas for renewable fuel production. The Department is encouraged to support the further development of renewable hydrocarbon fuels from low-cost waste CO2 and low-carbon renewable energy.” – listed under the EERE description

“The Committee supports the integrated carbon and energy management activities of NE and EERE and provides $2,000,000 for Hybrid Carbon Conversion activities within Fossil Energy” and “The Department is encouraged to fund activities that promote the reuse of captured carbon from coal for the production of fuel and other valuable products.”– stated under Coal-CCS and Power Systems

**Senate:** “The Committee encourages the Bioenergy Technologies Office to continue its collaboration with the Office of Fossil Energy on BECCS research, as well as research to advance net carbon-negative transportation fuels.” – in BETO’s section

“The Committee encourages the Office of Fossil Energy to collaborate with the Bioenergy Technologies program within EERE to support projects that utilize carbon dioxide” – stated under Coal-CCS and Power Systems

45Q Tax Credit Extension, $$ increase, and utilization included!
Summary: Carbon Reduction and Valorization Initiative through Fossil Energy and BETO Collaboration

Intersection of four technology developments:
1. Carbon Capture
2. Renewable Energy deployment
3. Bioengineering
4. Catalysis

CAISO curtailments
Ian Rowe, Ph.D.
Technology Manager | Bioenergy Technologies Office
U.S. Department of Energy
o. 202-586-7720 | Ian.Rowe@ee.doe.gov
@PowerhouseRowe
Biological Carbon Utilization

**Autotrophs:**
Use photosynthesis to convert light energy to chemical energy in the form of ATP. This ATP provides the energy needed to reduce CO$_2$ to glucose:

$$6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$$

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Use inorganic sources (H$_2$, NH$_3$, S, Fe$+2$) to generate ATP and reduce carbon
Office of Fossil Energy efforts in the Bioenergy space

Coal and Coal-Biomass-to-Liquids Program

- Convert coal to liquid fuels with biomass to reduce CO₂ emissions
- Mostly gasification/Fischer-Tropsch
- Slated to end under FY18 budget

Carbon Use and Reuse Technology Area

- Develop technologies identified as having the greatest potential to help boost the commodity market for CO₂ while producing no additional CO₂ emissions.
- Biological efforts in CO₂ use are relatively new and are mainly algae
- 7 projects, approximately $6.5M total

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Michigan State: CAP for a novel CO2 capture solution and polyurethane composites ($1.25M)

Uni of Illinois: PBR algal growth with dewatering membrane development ($1.25M)
Other DOE efforts in CO₂ Utilization

**BETO Algae Program:**
- Funding: ~$30M/yr
- Recent PEAK FOA focused on toolkits to increase productivity from around 10 to 20 g/m²/d to get overall cost down from roughly $900/t to $500/t

**BETO Conversion Program:**
- Funding: Less than $5M total
- Lanzatech, Kiverdi: Convert waste CO/H₂ into alcohols or terpenes
- White Dog Labs: Mixotrophic fermentation of 2nd gen sugars using the Wood-Ljungdahl pathway

**ARPA-E ELECTROFUELS Program:**
- Funding: $50M from 6/2010 thru 12/2014
- Non-photosynthetic microbes transform CO₂ into fuels while using electricity to provide the energy needed to fix carbon.
Relevant Budget Language:

**House:** “The Committee is aware of the significant benefits from the further development of electrochemical conversion of CO2 to syngas for renewable fuel production. The Department is encouraged to support the further development of renewable hydrocarbon fuels from low-cost waste CO2 and low-carbon renewable energy.” – listed under the EERE description

“The Committee supports the integrated carbon and energy management activities of NE and EERE and provides $2,000,000 for Hybrid Carbon Conversion activities within Fossil Energy” and “The Department is encouraged to fund activities that promote the reuse of captured carbon from coal for the production of fuel and other valuable products.” – stated under Coal-CCS and Power Systems

**Senate:** “The National Academies of Sciences, Engineering, and Medicine has recognized that bioenergy with carbon capture sequestration [BECCS] has technical potential to provide a significant portion of the world’s energy supply by the end of the century. If commercialized further, BECCS could be a baseload electricity resource with a net-negative carbon emission profile. The Committee encourages the Bioenergy Technologies Office to continue its collaboration with the Office of Fossil Energy on BECCS research, as well as research to advance net carbon-negative transportation fuels.” – in BETO’s section

“The Committee encourages the Office of Fossil Energy to collaborate with the Bioenergy Technologies program within EERE to support projects that utilize carbon dioxide in the production of algae and other potentially marketable products.” – stated under Coal-CCS and Power Systems