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

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Office of Fossil Energy and Bioenergy Technologies Office
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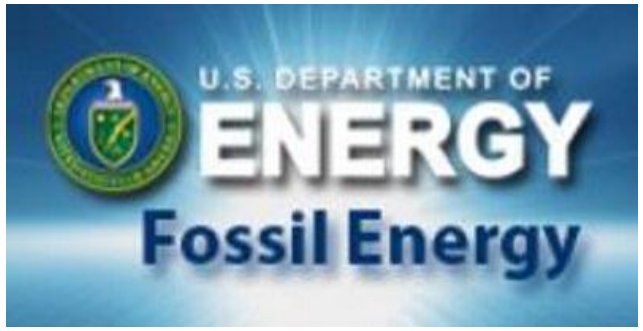
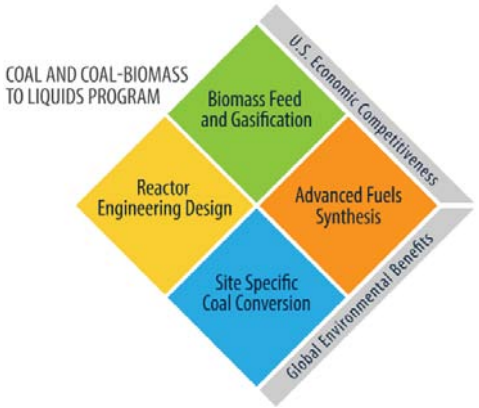


What I wont be addressing:

Coal and Coal-Biomass-to-Liquids Program

- Convert coal to liquid fuels with biomass to reduce CO_2 emissions
- Mostly gasification/Fischer-Tropsch
- Slated to end under FY18 budget

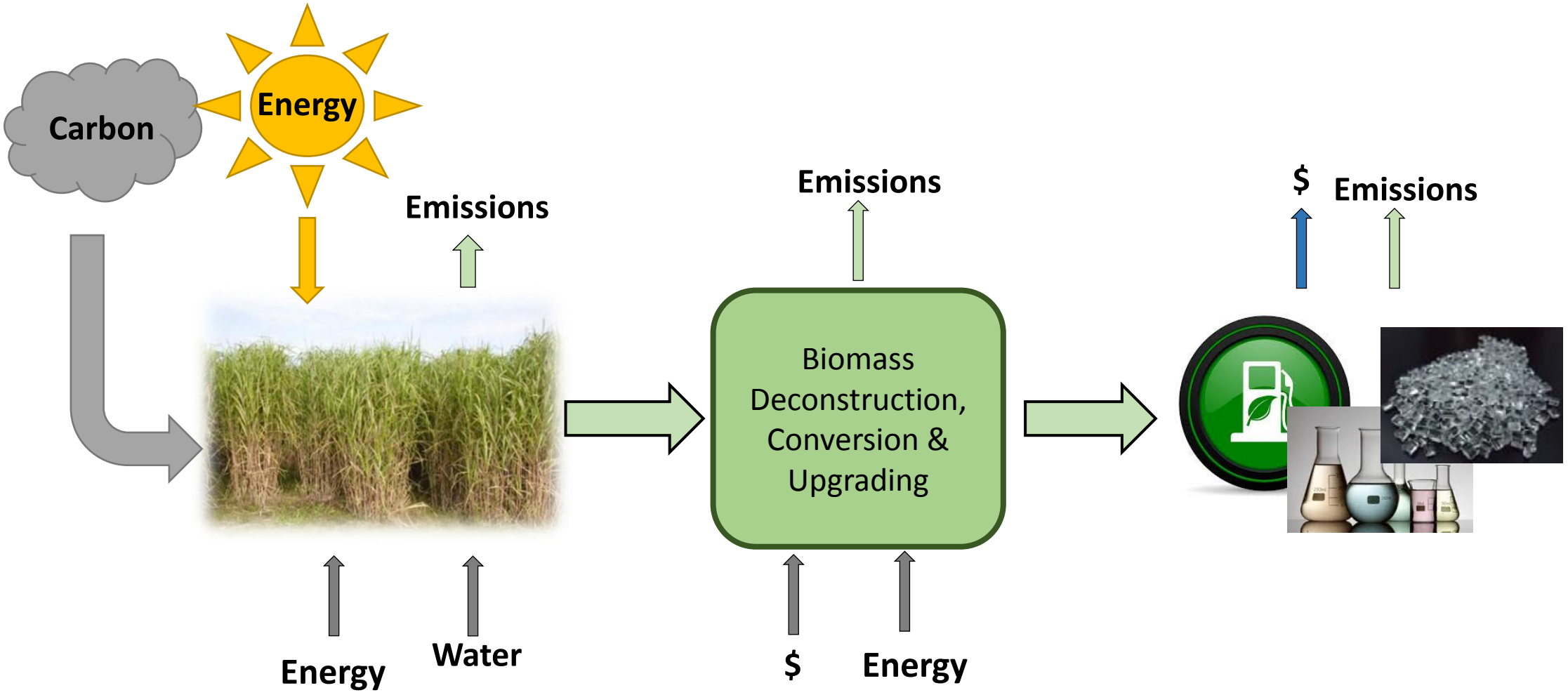


DE-FOA-0001622: Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants.

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

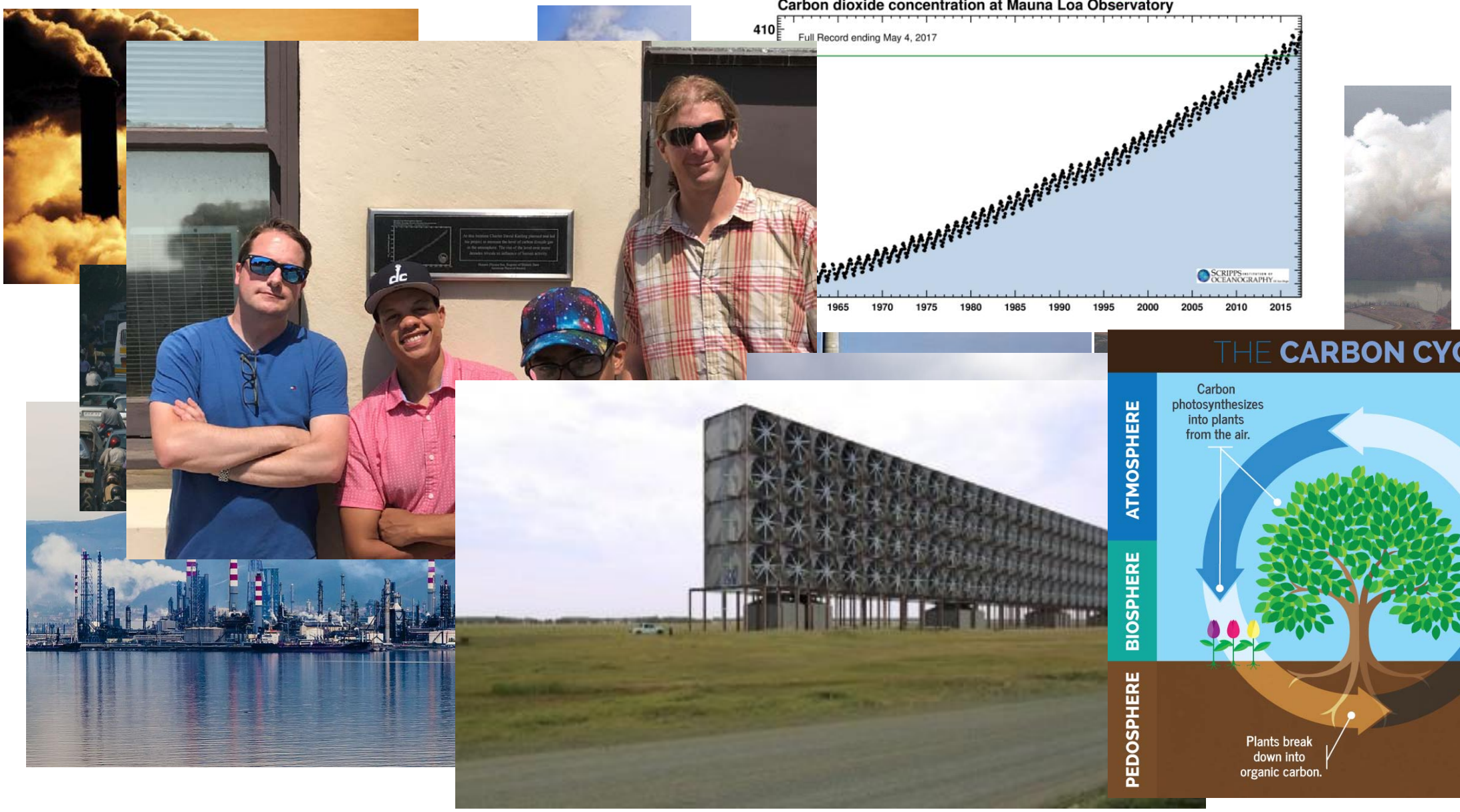
USDA CERTIFIED BIOBASED PRODUCT

Food vs Fuel

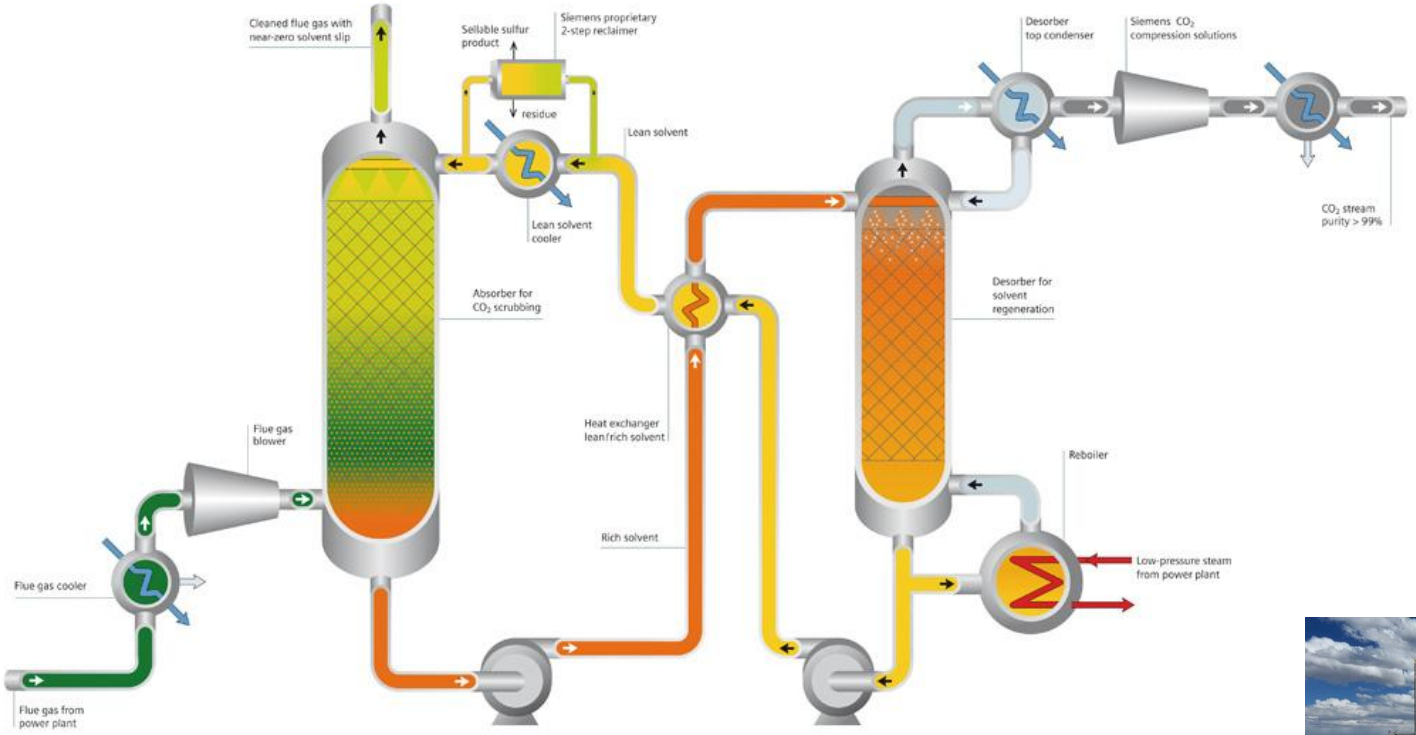
Food vs Products

- 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!



Carbon Capture and Sequestration



Carbon capture unit flow diagram

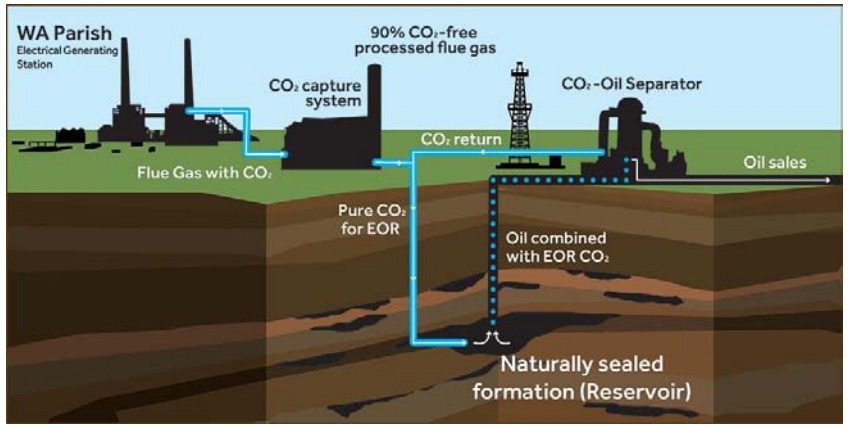
9 large scale CCS units in operation in the US

- 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

Shute Creek, WY (7 Mtpa)

ADM, IL (1 Mtpa)

Carbon Capture and Sequestration in the power sector



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

FOSSIL FUELS

Carbon Capture Suffers a Huge Setback as Kemper Plant Suspends Work

It's the latest U.S. government-supported boondoggle around CCS.

by Katie Fehrenbacher
June 29, 2017

THE COST OF CARBON CAPTURE

Jeremy David and Howard Herzog
Massachusetts Institute of Technology (MIT), Cambridge, MA, USA

CONCLUSION

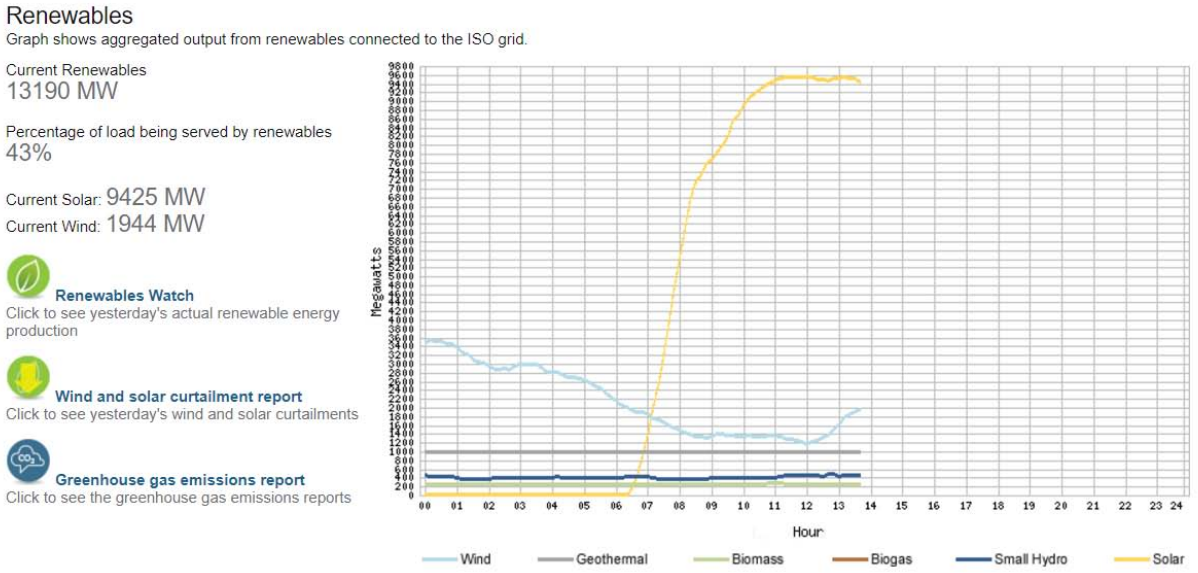
Based on the studies analyzed, there is a consensus that using today's capture technology would add 1.5-2¢/kWh to the busbar cost of electricity for an IGCC or NGCC power plant. For a PC plant, the incremental cost of electricity would be over 3¢/kWh. The strongest opportunities for lowering the capture costs in the future were identified as gains in heat rates and reductions in the amount of energy required by the separation. New technologies like coal gasification show the

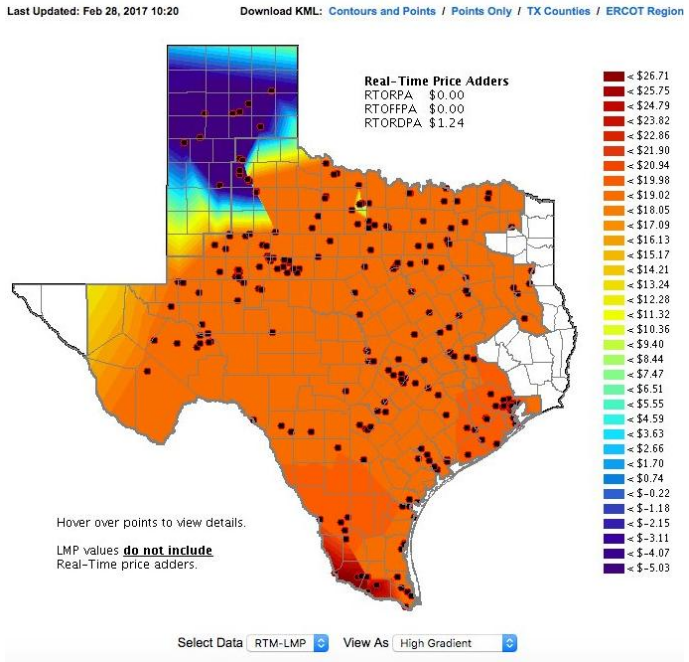
- CCS is a great tool, demonstrated to work
- Too expensive
- Needs enabling technology

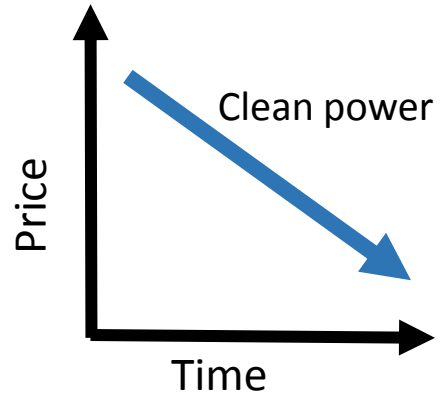
Renewable Energy Deployment is picking up

Period	Coal	Petroleum Liquids	Petroleum Coke	Natural Gas	Other Gas	Nuclear	Hydroelectric Conventional	Solar	Renewable Sources Excluding Hydroelectric and Solar	Hydroelectric Pumped Storage	Other	Total Generation at Utility Scale Facilities
Year 2017												
January	115,549	1,175	945	91,325	1,115	73,121	27,704	2,206	27,232	-418	1,118	341,072
February	87,267	916	707	78,581	1,152	64,053	24,611	2,562	28,045	-504	1,024	288,414
March	89,648	971	744	92,638	1,206	65,093	30,198	4,474	32,399	-517	1,078	317,934
April	81,789	897	435	86,234	1,084	56,743	29,236	4,816	31,821	-437	1,061	293,679
May	93,125	1,002	839	96,354	1,163	61,309	32,122	5,816	28,815	-423	1,080	321,202

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 CO2** to glucose:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

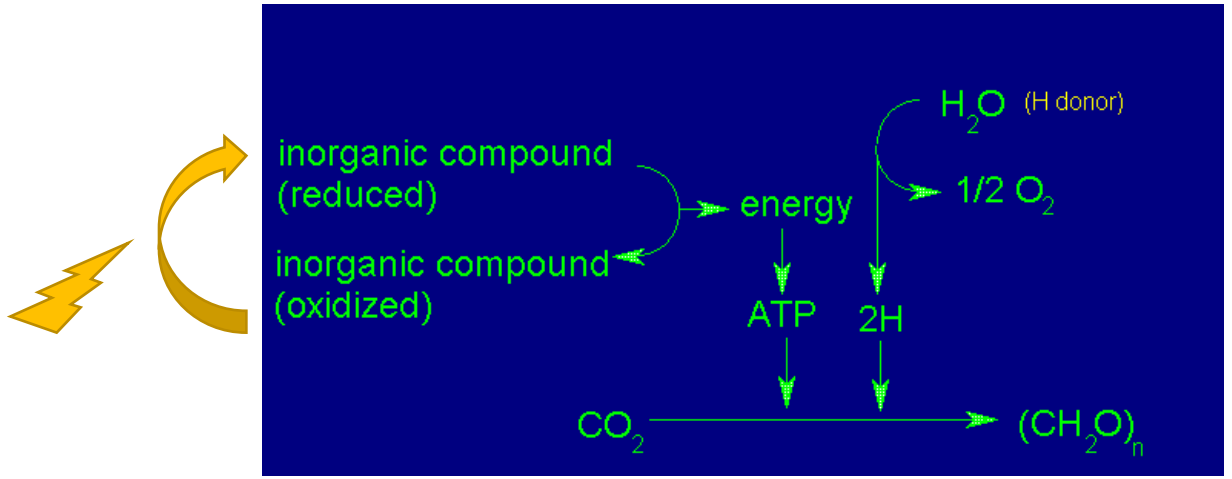
Heterotrophs:

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

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Chemolithoautotrophs:

Use inorganic sources (H2, NH3, S, Fe+2) to generate ATP and reduce carbon



ELECTROFUELS: Renewable H2 as the source of reductant

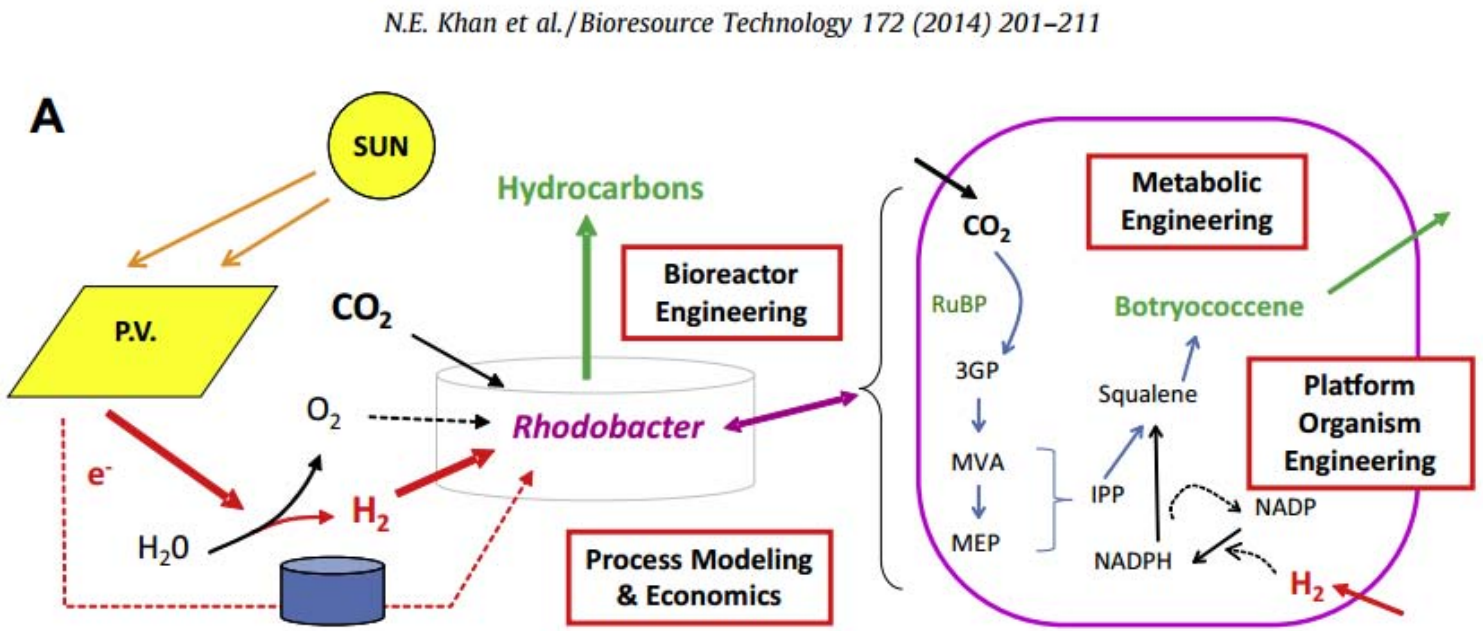
7 Projects, totaling $23.8M

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

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

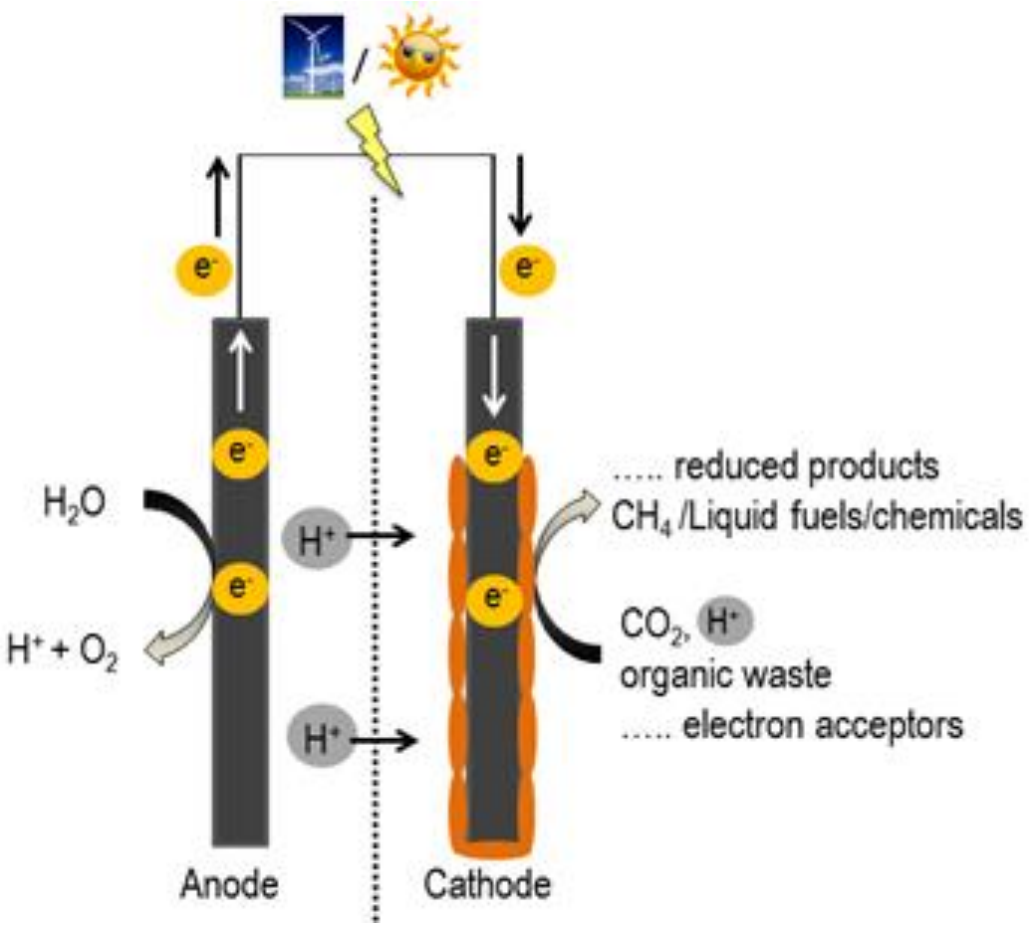
ELECTROFUELS: Using electricity more directly

4 Projects, totaling $14M

Project	Awardee	$$, M
Electrofuels Via Direct Electron Transfer from Electrodes to Microbes	Umass Amherst	5.6
Engineering a Bacterial Reverse Fuel Cell	Harvard	4.2
Electroalcoholgenesis: Bioelectrochemical Reduction of CO2 to Butanol	MUSC	2.7
Biofuels from CO2 Using Ammonia or Iron-Oxidizing Bacteria in Reverse Microbial Fuel Cells	Columbia U.	1.5

ELECTROFUELS: Using electricity more directly

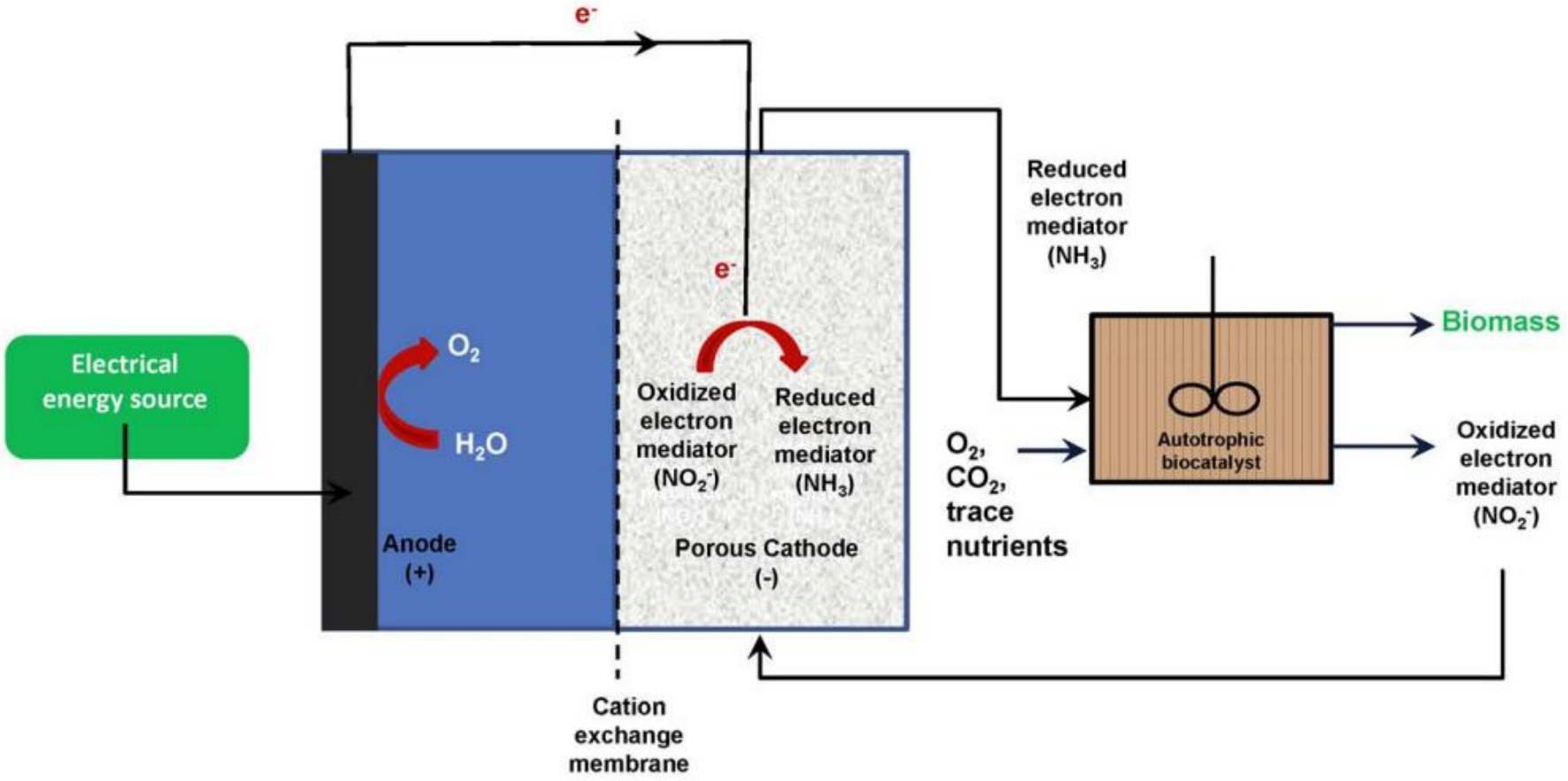
Umass Amherst: Electrofuels via Direct Electron Transfer from Electrodes to Microbes ($5.6M)



- acetogenic *Clostridium*
- Form bio-films on electrodes
- Organism directly uses electrons to power the CO2 reduction

ELECTROFUELS: Using electricity more directly

Columbia: Biofuels from CO2 Using NH3 Oxidizing Bacteria in Reverse Microbial Fuel Cells ($1.5M)



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

Project	Awardee	$$, M
Engineering E. coli as an Electrofuels Chassis for Isooctane Production	Ginkgo Bioworks	6.7
Electro-Autotrophic Synthesis of Higher Alcohols	UCLA	4.2

ELECTROFUELS: reducing carbon via electricity

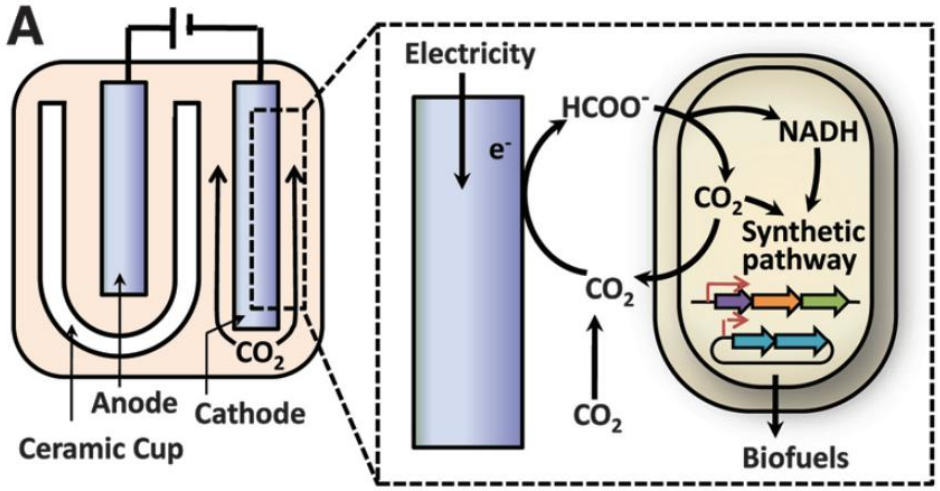
UCLA: Electro-Autotrophic Synthesis of Higher Alcohols ($4.2M)

Electrocatalytic Reduction

CO2 ⇨ Formic Acid

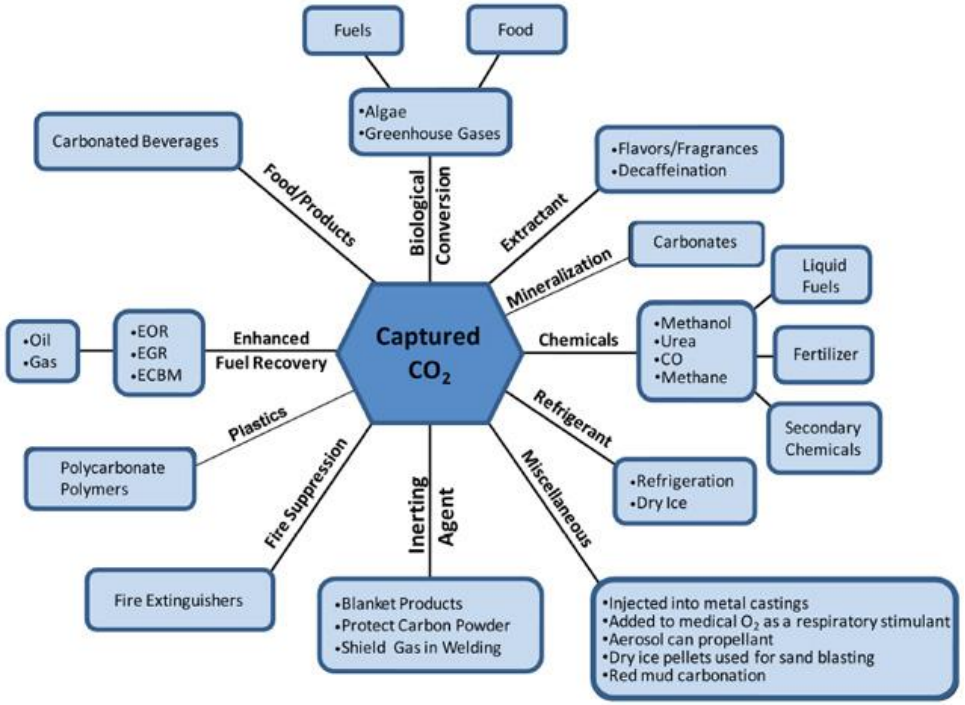
Biological Upgrading

Formic Acid ⇨ Butanol



- 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 CO_2 Conversion Powered by Renewable Energy

Douglas R. Kauffman,*,† Jay Thakkar,† Rajan Siva,† Christopher Matranga,† Paul R. Ohodnicki,† Chenjie Zeng,‡ and Rongchao Jin‡

†National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, Pennsylvania 15236, United States
‡Department of Chemistry, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States

Supporting Information

ABSTRACT: The catalytic conversion of CO_2 into industrially relevant chemicals is one strategy for mitigating greenhouse gas emissions. Along these lines, electrochemical CO_2 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

NETL

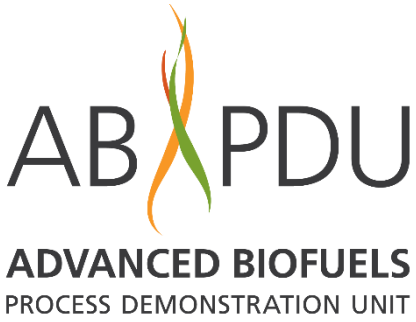
High Efficiency Solar-based Catalytic Structure for CO_2 Reforming

Background

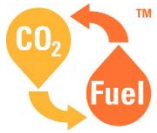
NETL

Chemical Fixation of CO_2 to Acrylates Using Low-Valent Molybdenum Sources

BETO has a vast portfolio of bioengineering expertise



Current electrocatalytic and biological technologies available



Dioxide Materials™
The CO_2 Recycling Company™

LanzaTech
capturing carbon fueling growth

OPUS 12

DNV·GL

NCF
New CO_2 Fuels

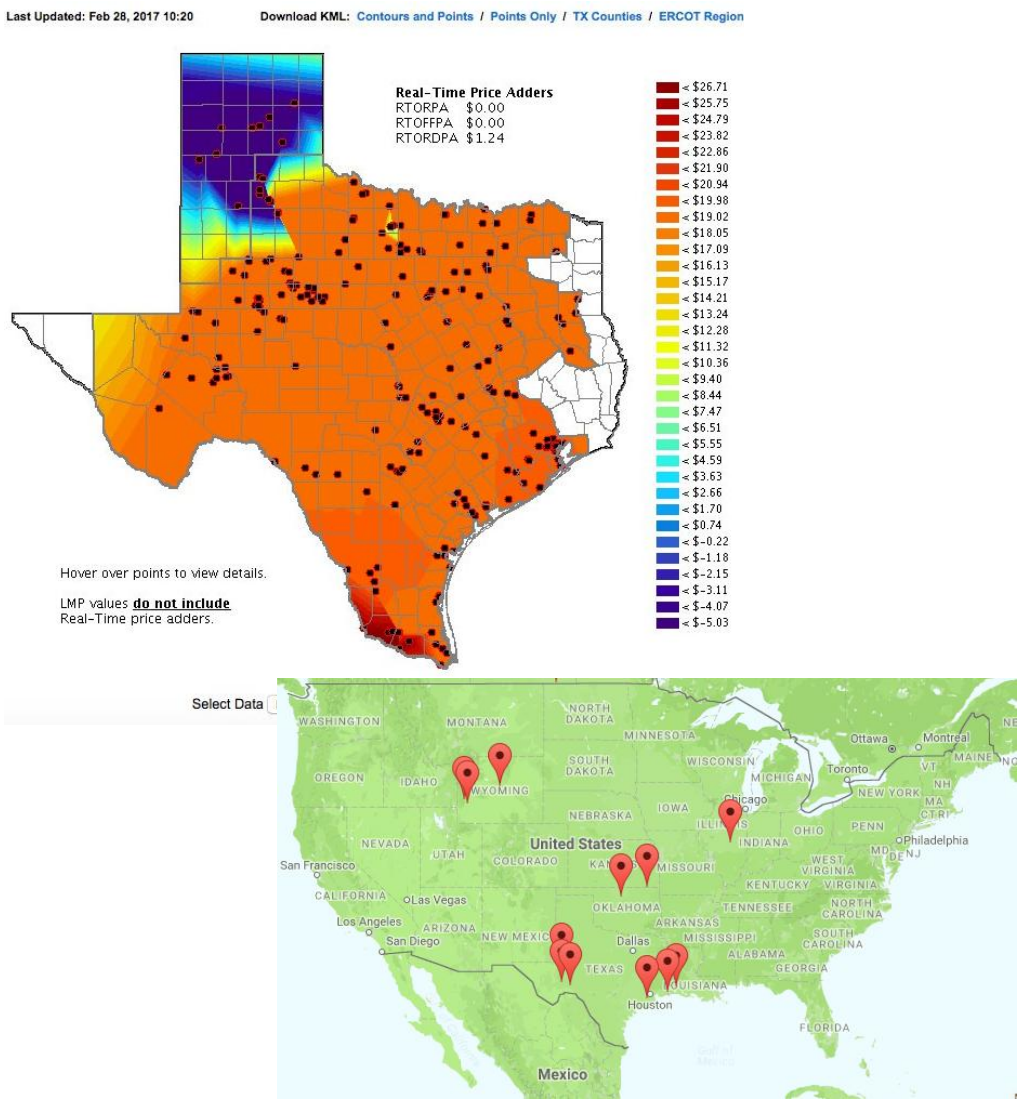
Kiverdi

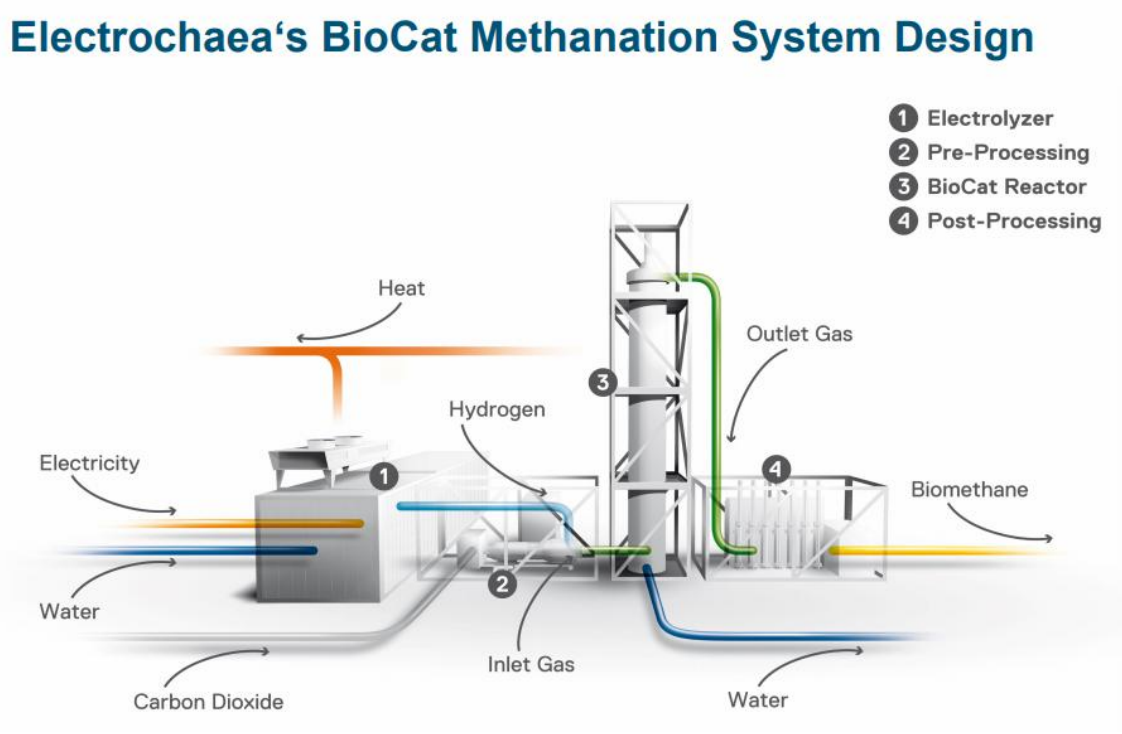
INEOS

LIQUIDLIGHT

CARBON RECYCLING INTERNATIONAL

Rewiring carbon reduction to enable grid reliability and energy storage





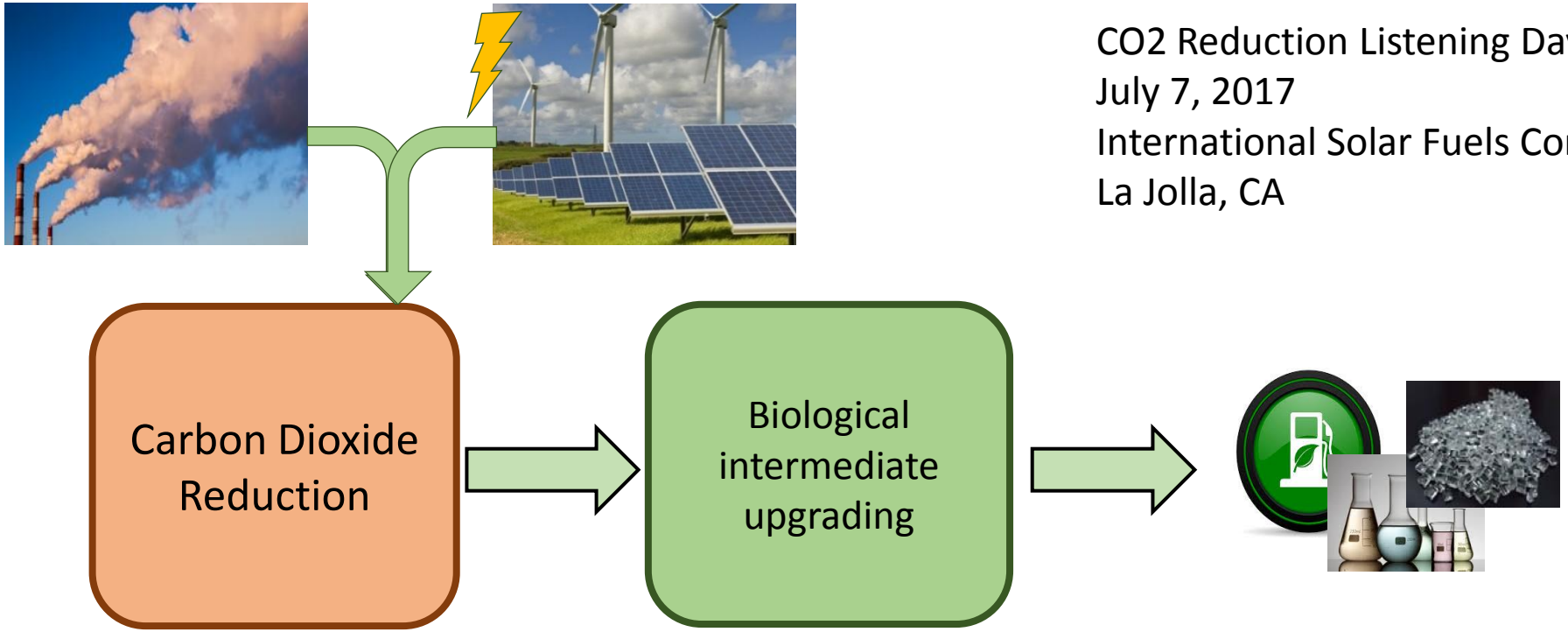
Early progress in the Carbon Reduction and Valorization Initiative

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

Non-photosynthetic carbon reduction	
Opus 12 Incorporated	Utilization of waste CO_2 to make renewable chemicals and fuels
Reactive Innovations, LLC	Novel Cold Plasma System for the Reaction of CO_2 and Liquid Feed Streams for the Production of Value Added Products
Sustainable Innovations, LLC	Renewables-Driven Production of Organic Acids from Industrial CO_2 Waste Streams
Visolis, Inc	Production of High Value Products from Gaseous Waste Streams

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

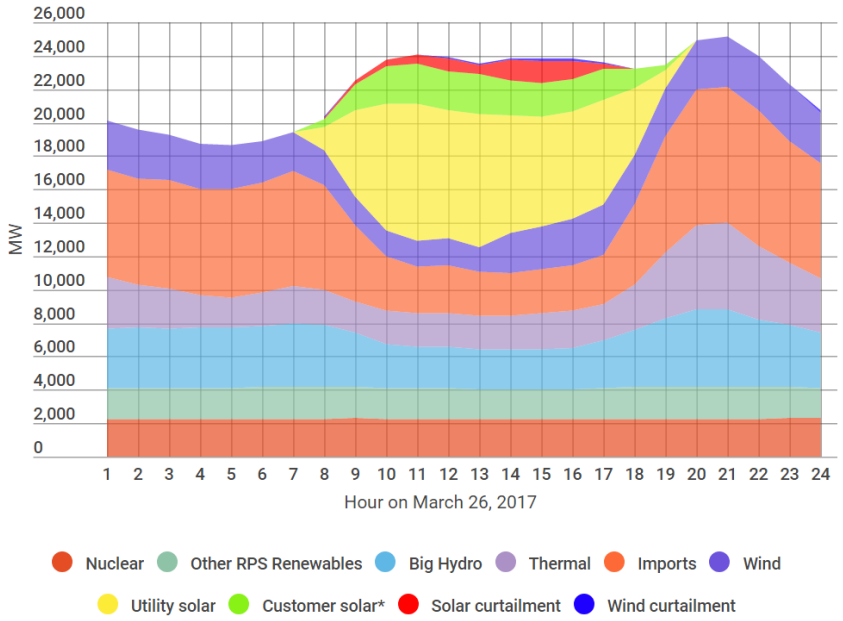
"*The Committee encourages the Office of Fossil Energy to collaborate with the Bioenergy Technologies program within EERE to support projects that utilize carbon dioxide*" – stated under Coal-CCS and Power Systems

45Q Tax Credit Extension, $$ increase, and utilization included!

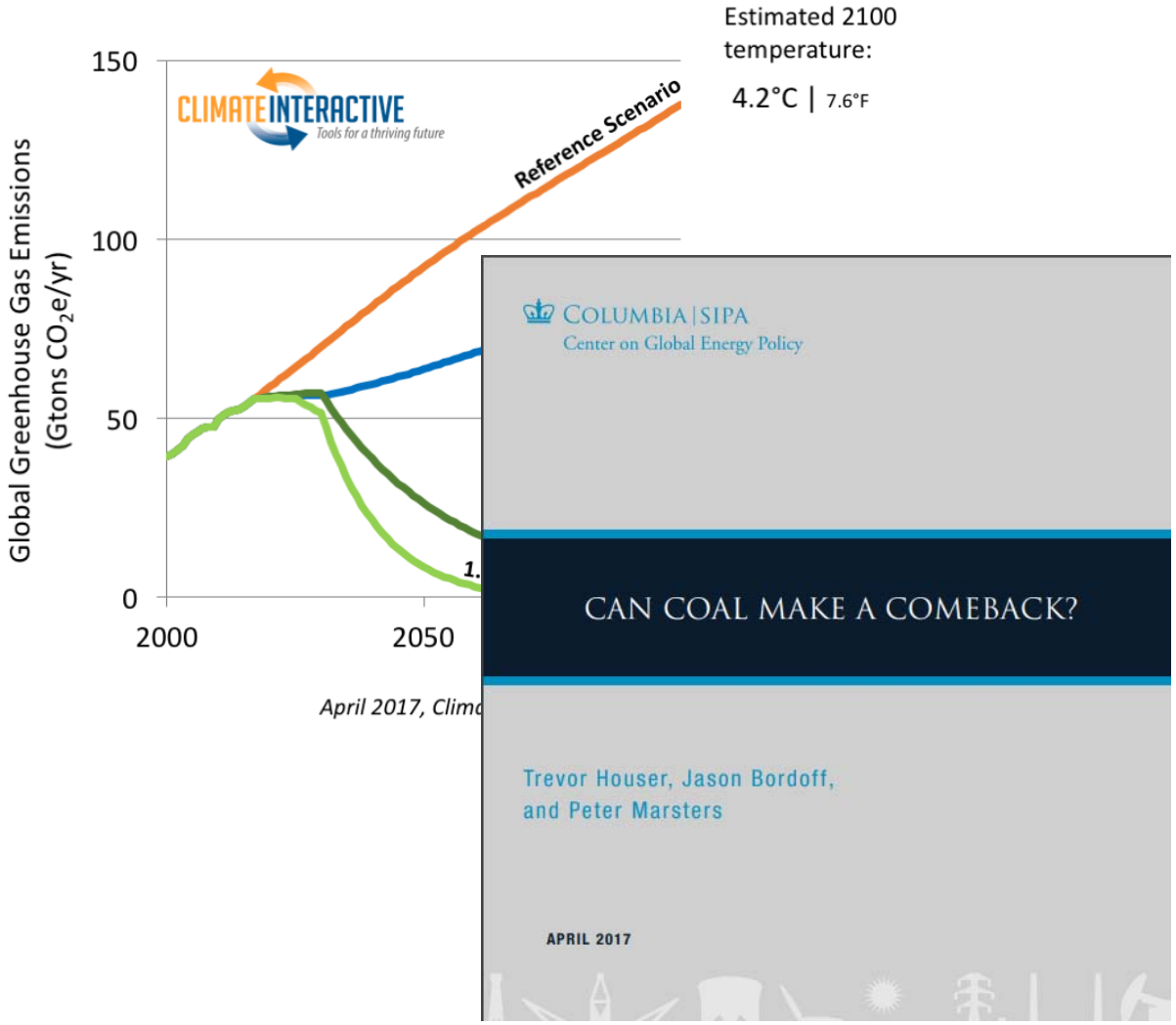
Summary: Carbon Reduction and Valorization Initiative through Fossil Energy and BETO Collaboration

Intersection of four technology developments:

1. Carbon Capture
2. Renewable Energy deployment
3. Bioengineering
4. Catalysis



CAISO curtailments



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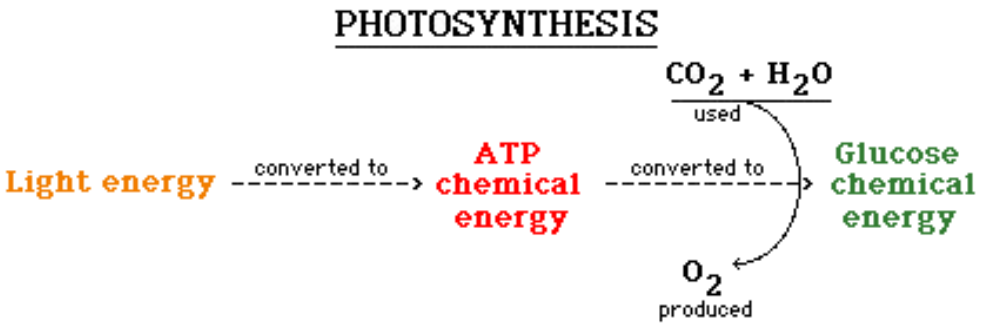
@PowerhouseRowe

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 CO2** to glucose:

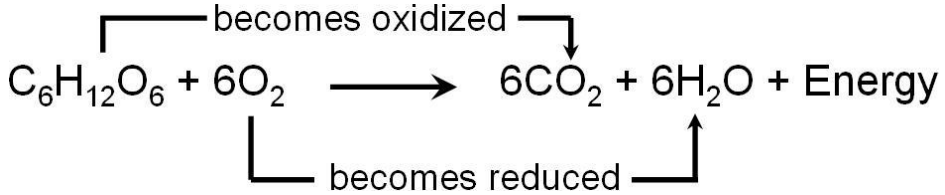
$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$



Heterotrophs:

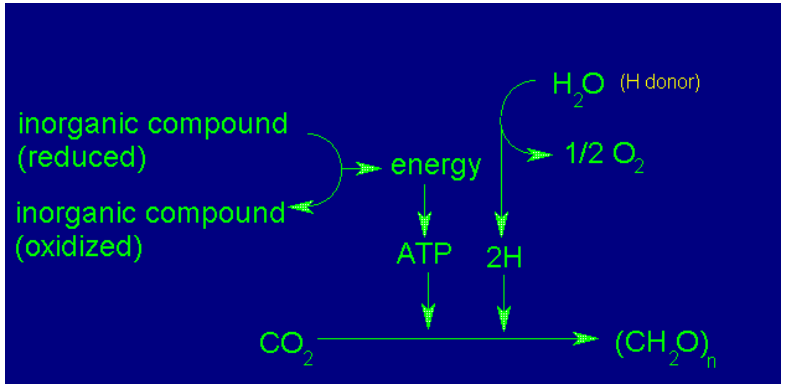
Use that **reduced carbon** originally generated by autotrophs in cellular respiration to produce ATP:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$



Chemolithoautotrophs:

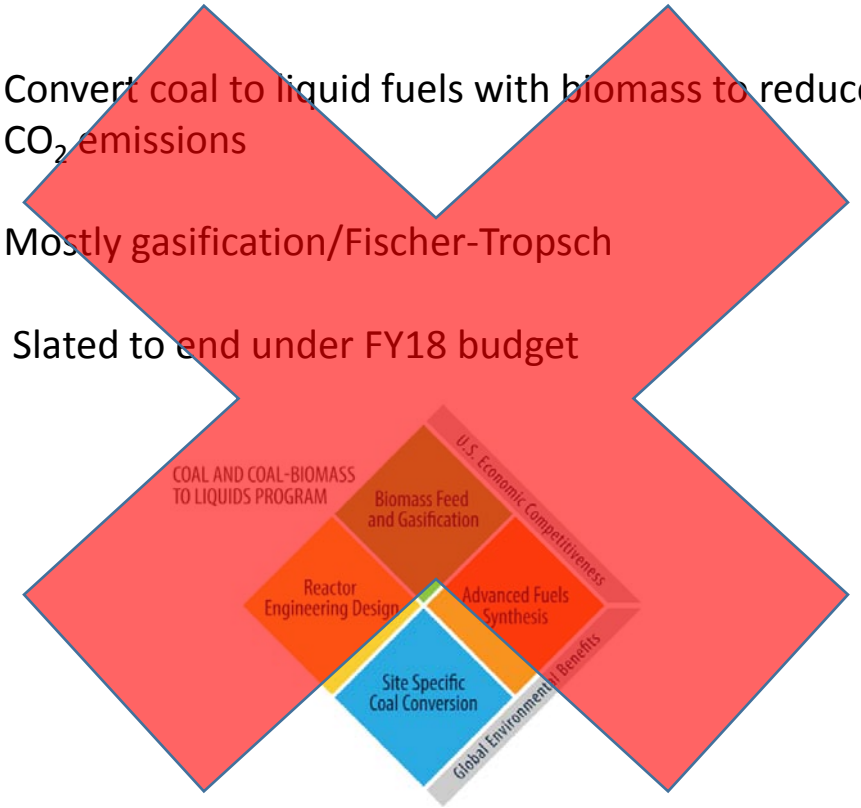
Use inorganic sources (H2, NH3, S, Fe+2) to generate ATP and reduce carbon



Office of Fossil Energy efforts in the Bioenergy space

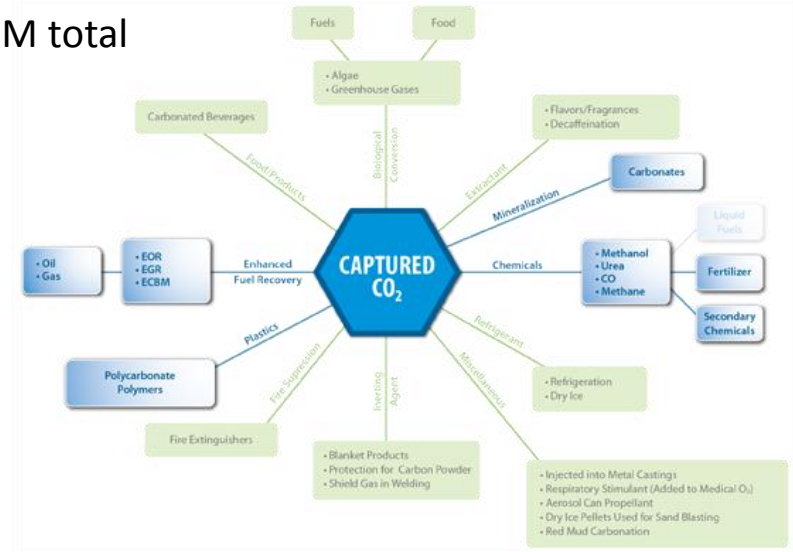
Coal and Coal-Biomass-to-Liquids Program

- Convert coal to liquid fuels with biomass to reduce CO_2 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 CO_2 while producing no additional CO_2 emissions.
- Biological efforts in CO_2 use are relatively new and are mainly algae
- 7 projects, approximately $6.5M total



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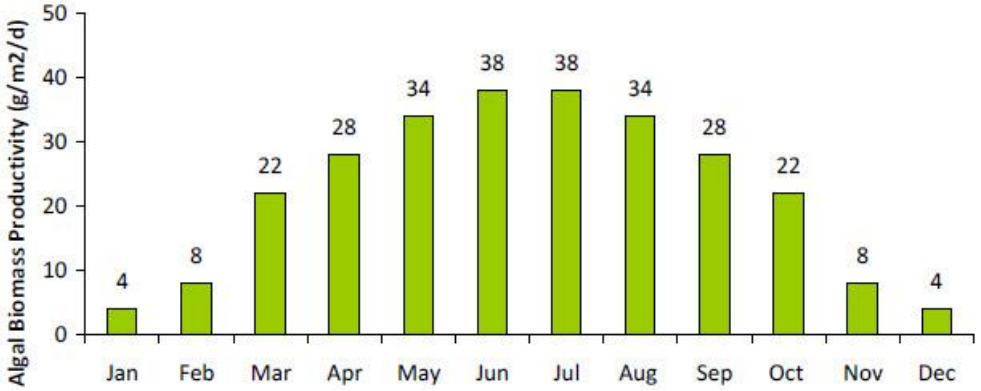
Michigan State: CAP for a novel CO2 capture solution and polyurethane composites ($1.25M)

Uni of Illinois: PBR algal growth with dewatering membrane development ($1.25M)

Other DOE efforts in CO_2 Utilization

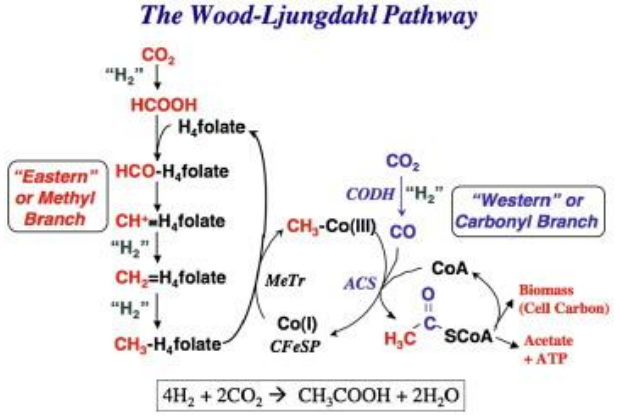
BETO Algae Program:

- 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 CO_2 into fuels while using electricity to provide the energy needed to fix carbon.

arpa·e
CHANGING WHAT'S POSSIBLE

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