Bioenergy Technologies Office Efforts in CO_2 utilization to generate fuels and chemicals

Carbon Utilization Project Review Meeting

October 22nd 2020

Ian Rowe

Technology Manager

Bioenergy Technologies Office

U.S. Department of Energy

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The Carbon Based Economy

We operate within a system that is carbon-based

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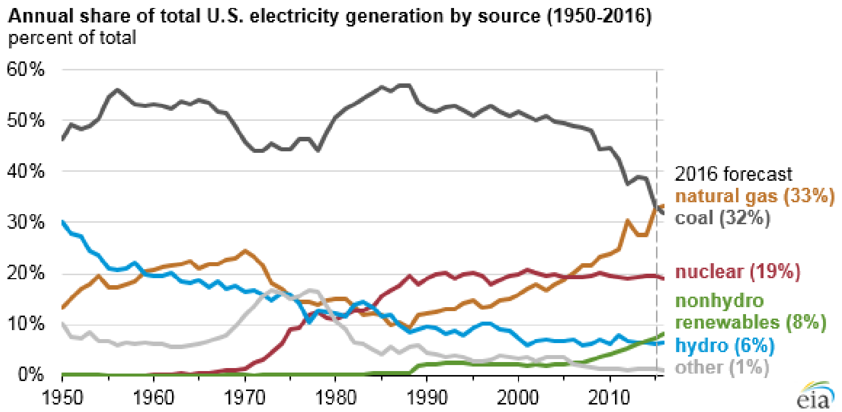
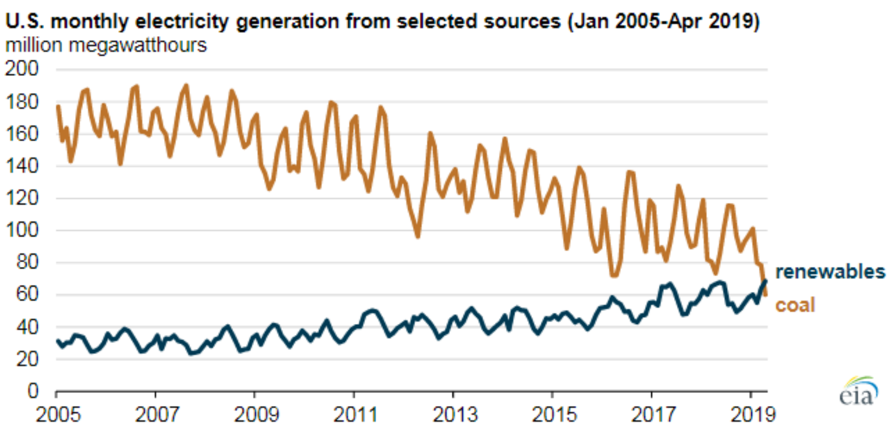
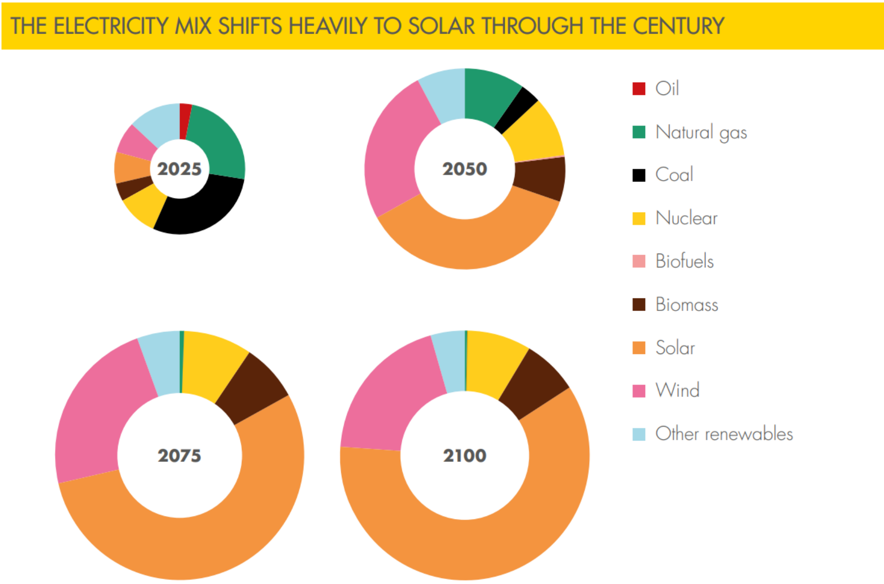
Increasing Penetration of Renewable Electricity







Note: The diameter of the pie chart represents the total electricity demand.
Source: Shell analysis

- The general trend is a reduction in the carbon intensity of the electricity sector

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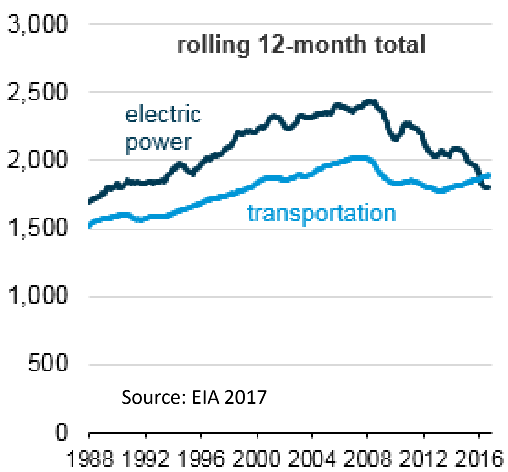
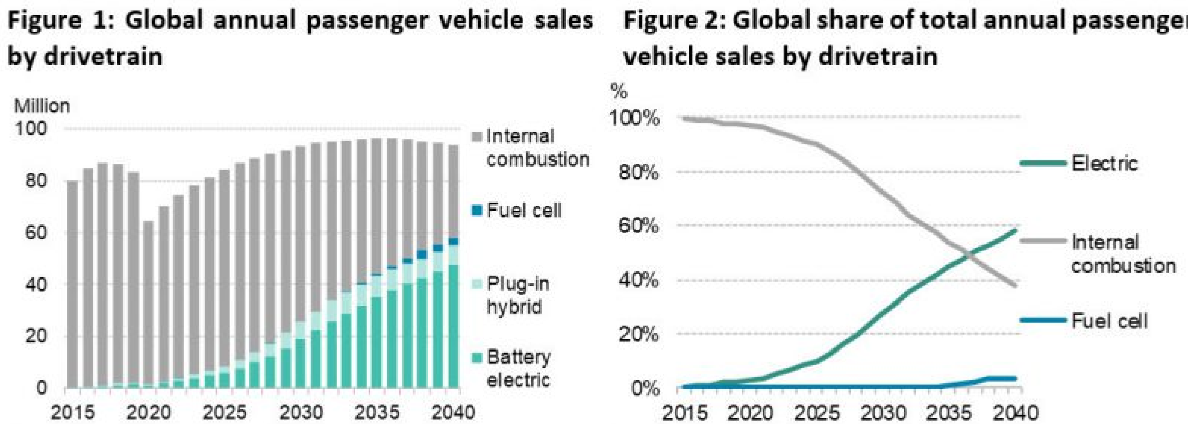
The Continued Importance of Liquid Carbon Fuels





Source: BNEF. Note: Electric share of annual sales includes battery electric and plug-in hybrid.

- A 1-hour flight on a 747-400 uses ~3,600 gal (11,000 kg) of jet fuel, which contains approximately 452,000 MJ of energy.
- Tesla Model S battery = ~0.75 MJ/kg
- Weight of 747-400: 184,000 kg
- **You'd need over 600,000 kg of battery for a 1-hour flight (over 3X the weight of plane)**

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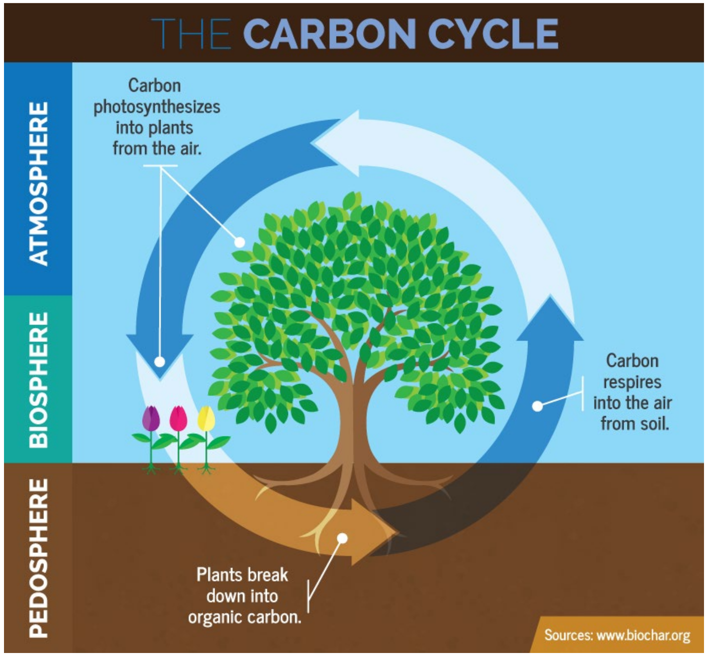
Bioenergy Technologies Office

- Develop ways to use our abundant renewable biomass resources to make biofuels and biobased products which are classically derived from petroleum

- ~$240M in FY20 funding
- Funds applied R&D work at DOE national labs and in the private sector/academia

- Divided into 5 Technology Programs:
  - Feedstock Supply and Logistics
  - Advanced Algal Systems
  - Conversion
  - Systems Development and Integration
  - Analysis and Sustainability

Obtaining, Managing, and Manipulating Renewable Carbon



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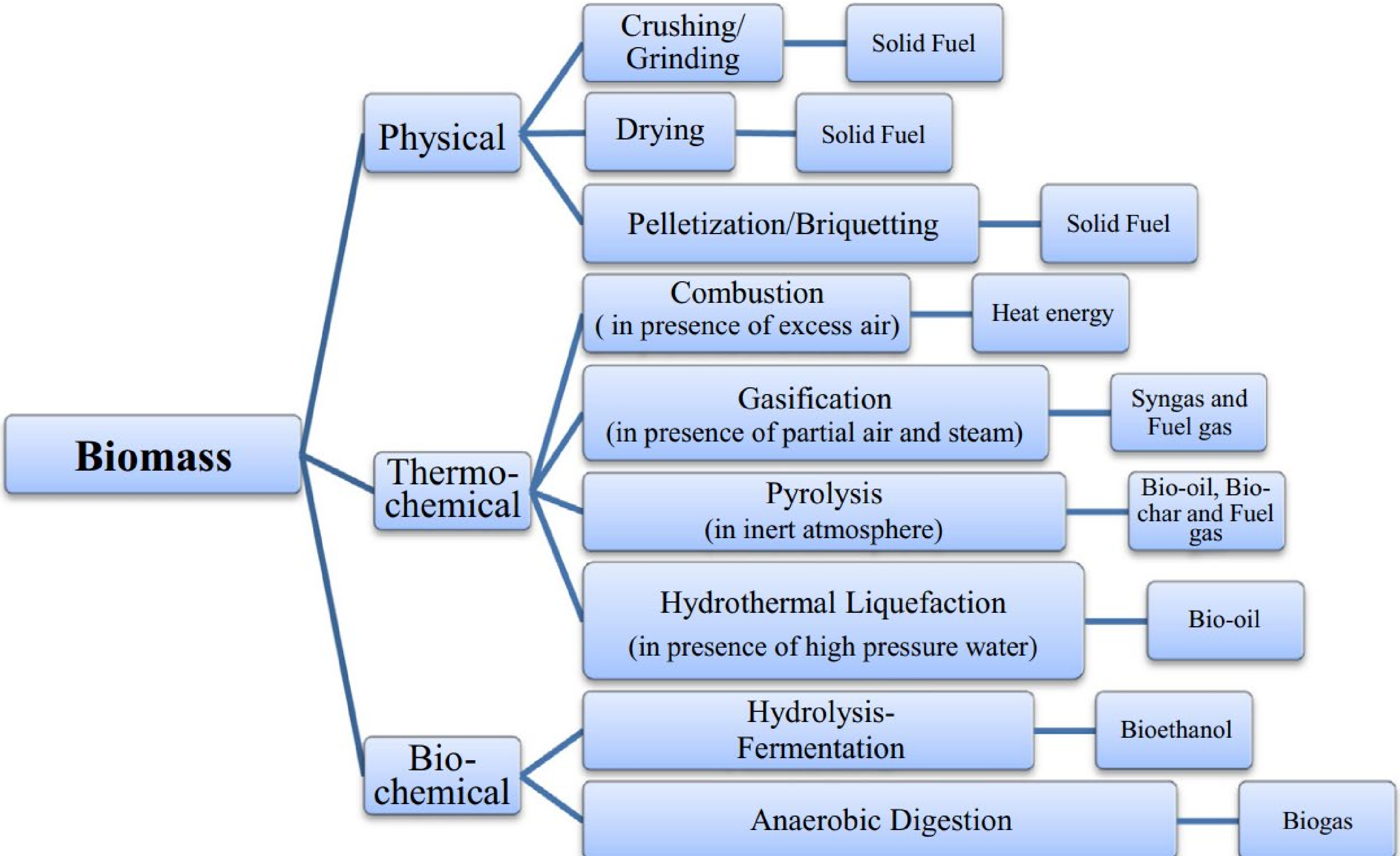
Converting Renewable Carbon to Fuels



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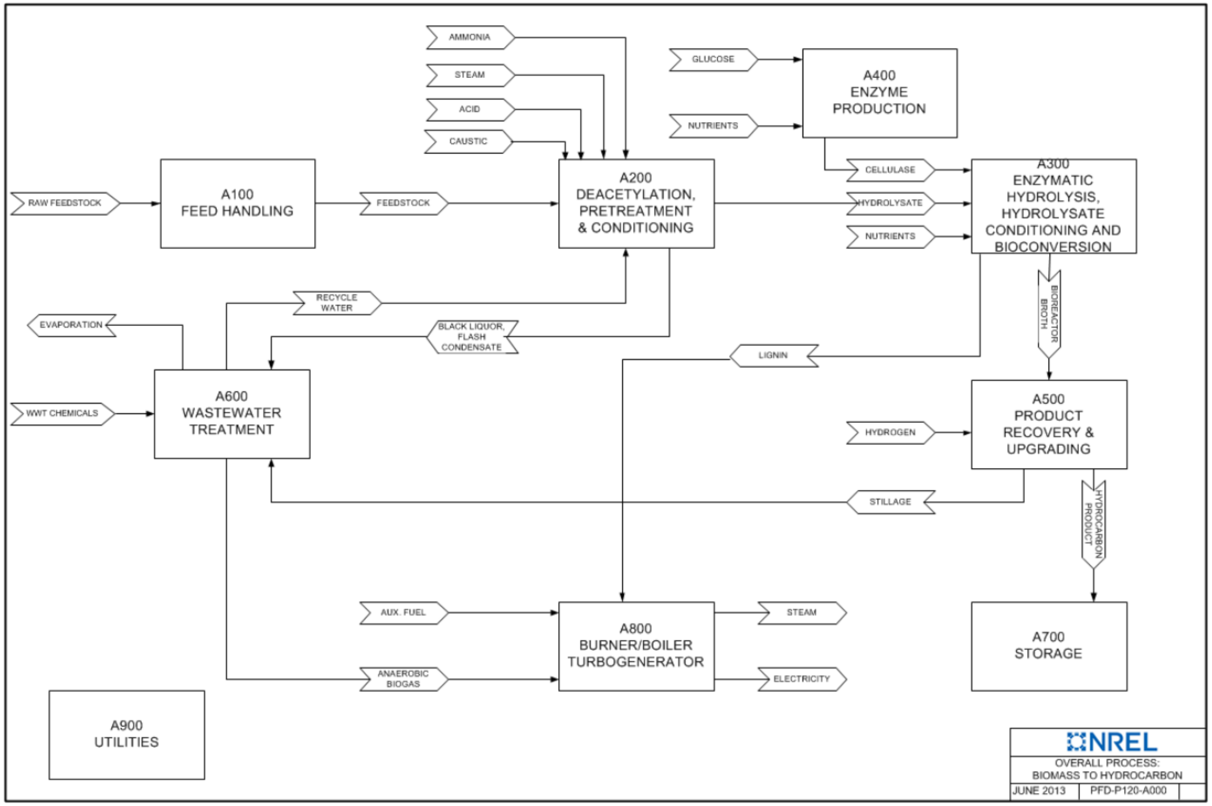
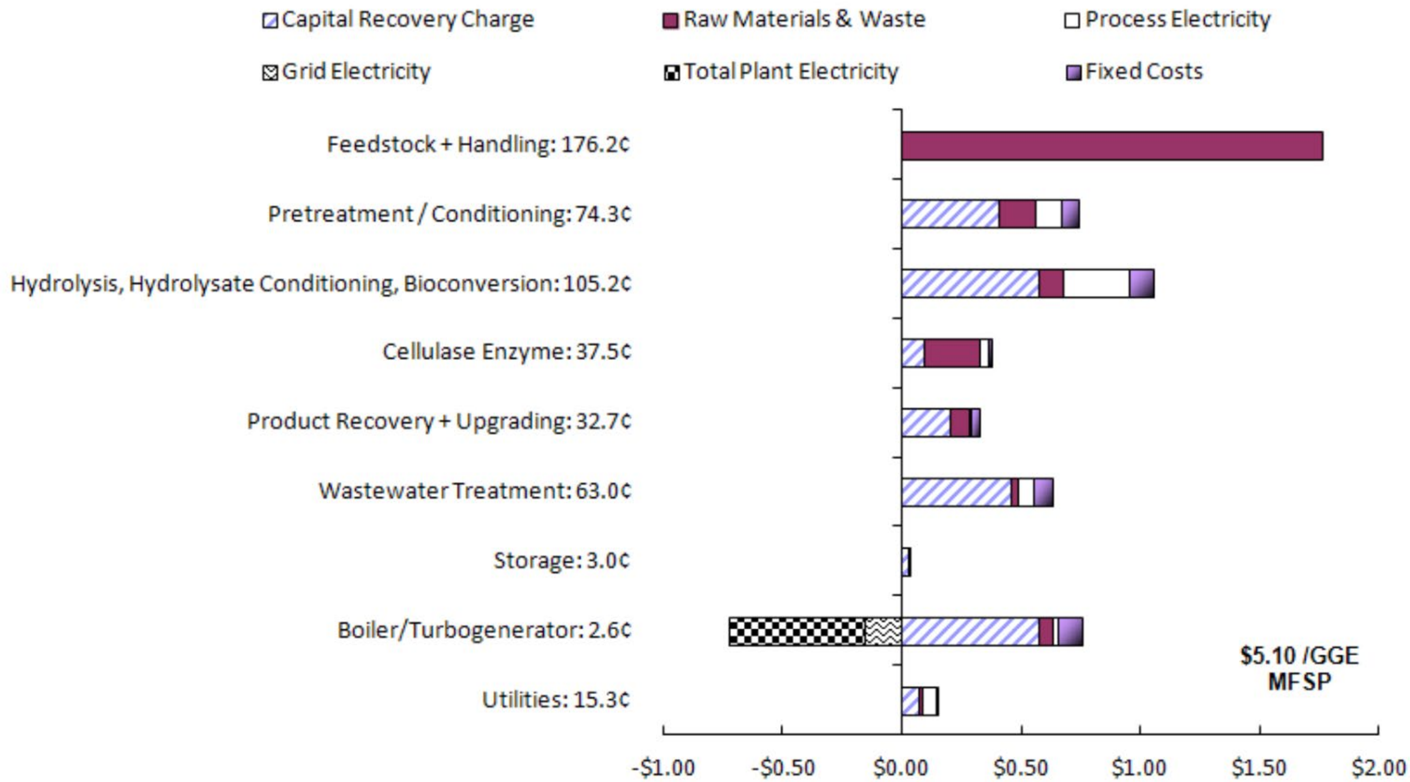
Comparing Technologies via Techno-Economic Analysis



Lignocellulosic biomass conversion to fuel

Comparing Technologies via Techno-Economic Analysis

Lignocellulosic biomass conversion to fuel



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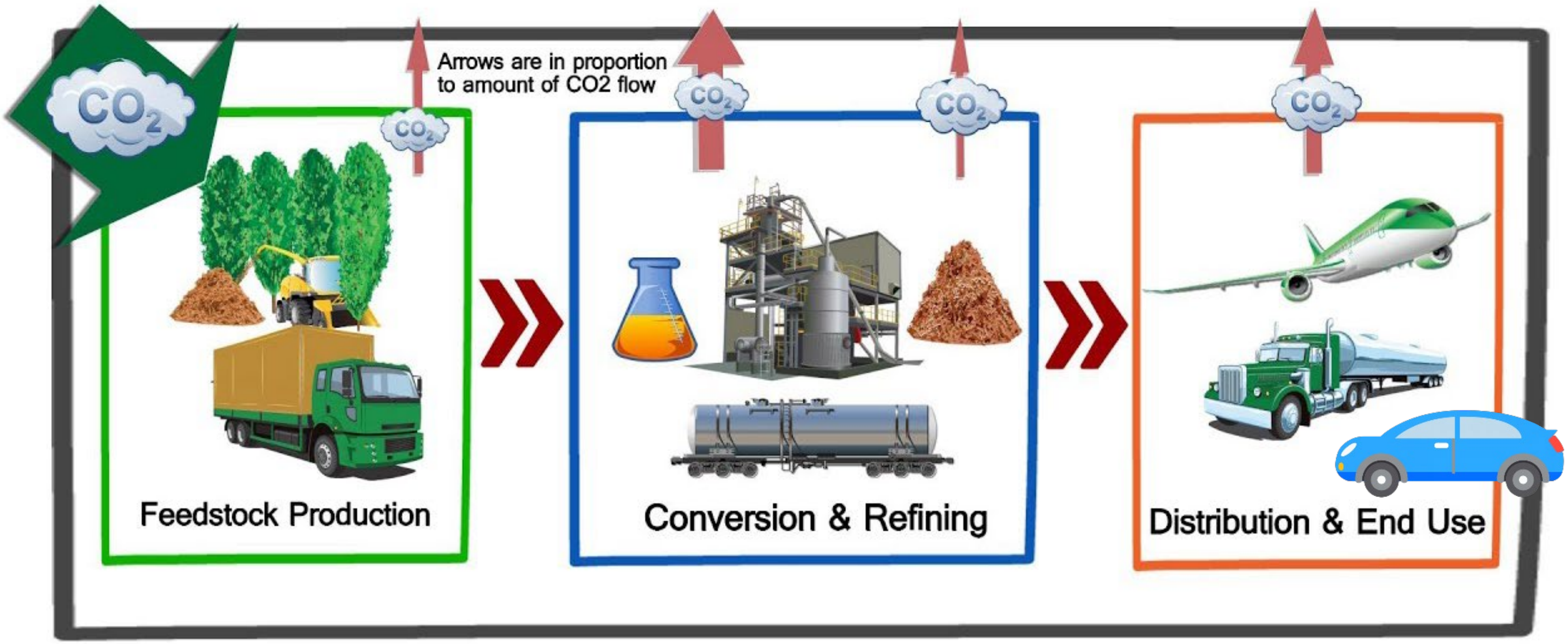
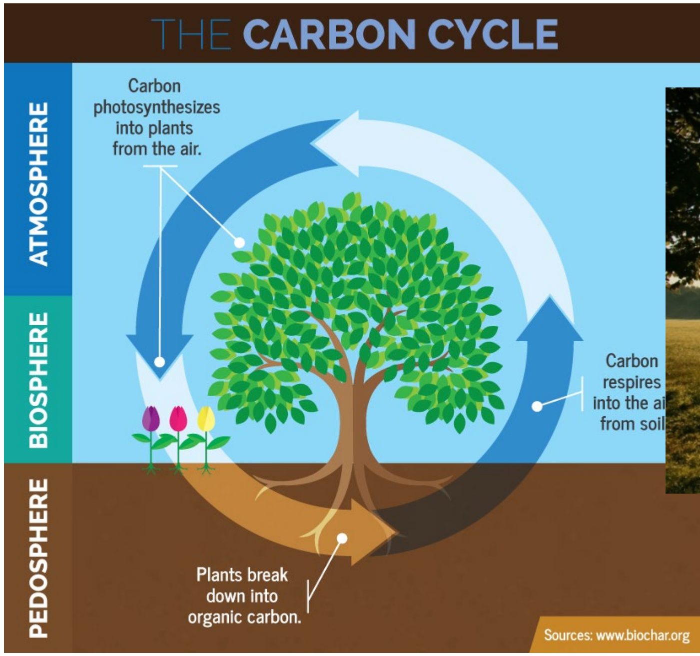
Comparing Technologies via Life Cycle Assessment

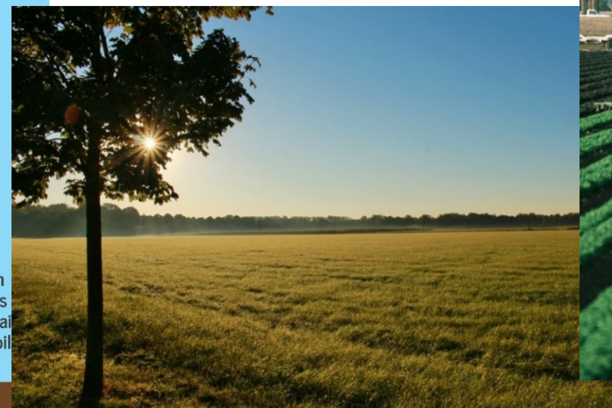


LCA System Boundary

Life cycle assessments provide a carbon intensity value associated with a fuel, which can be compared with a fossil incumbent

Expanding view of renewable carbon resources





Wet waste: 77M ton/yr

MSW in landfills: 140M ton/yr

Plastics: 35M ton/yr
<10% recycle rate

Waste CO_2: 5G ton/yr

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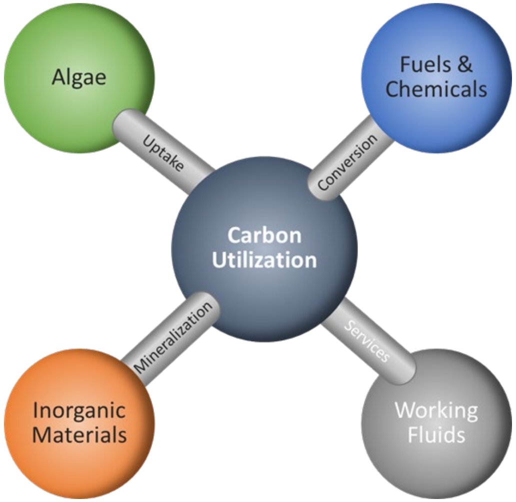
Other CO_2U Applied R&D

- Office of Fossil Energy "*Carbon Utilization*" sub-program within the "*Carbon Storage*" Program.



- BETO Advanced Algal Systems Program.
  - Tackles challenges along the supply chain—from increasing algae productivity via the application of advanced biological tools to the extraction and conversion of algal components

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

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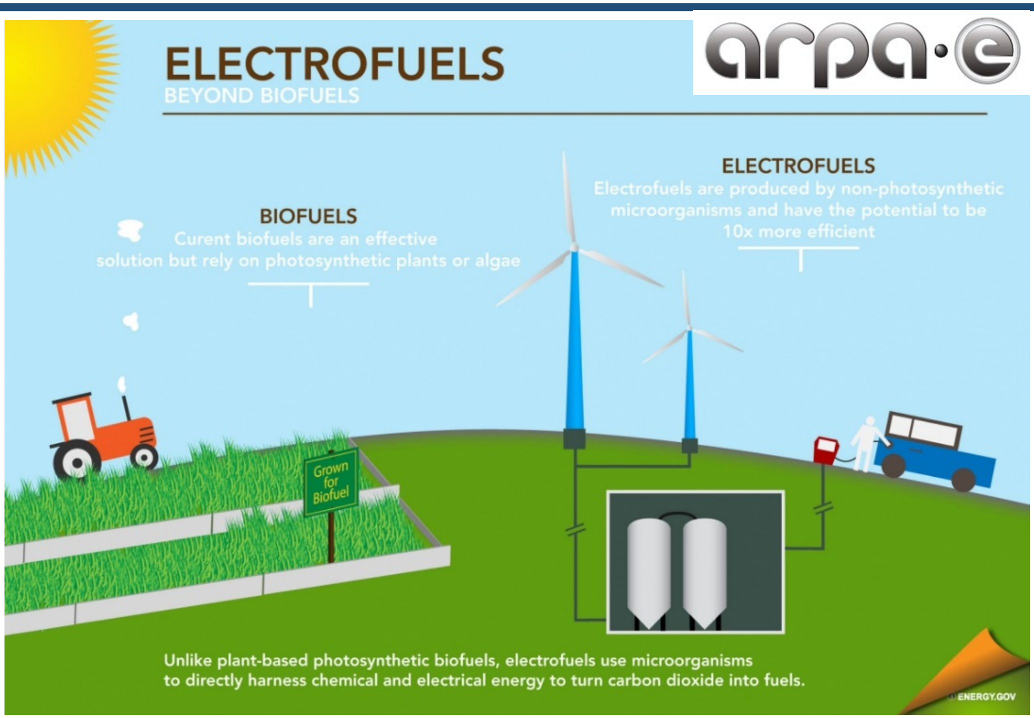
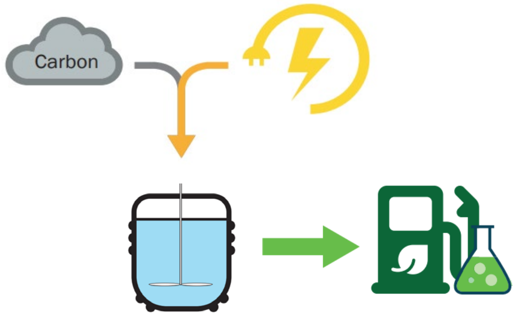
Applied R&D at ARPAe





ARPAe “ELECTROFUELS” route

- $50M in 12 projects from 2010 – 2014
- “Biology-on-an-electrode” approach to CO2U via chemolithoautotrophs
- Demonstrated the difficulties in microbial engineering and inherent rate limitation of bioelectrocatalysis

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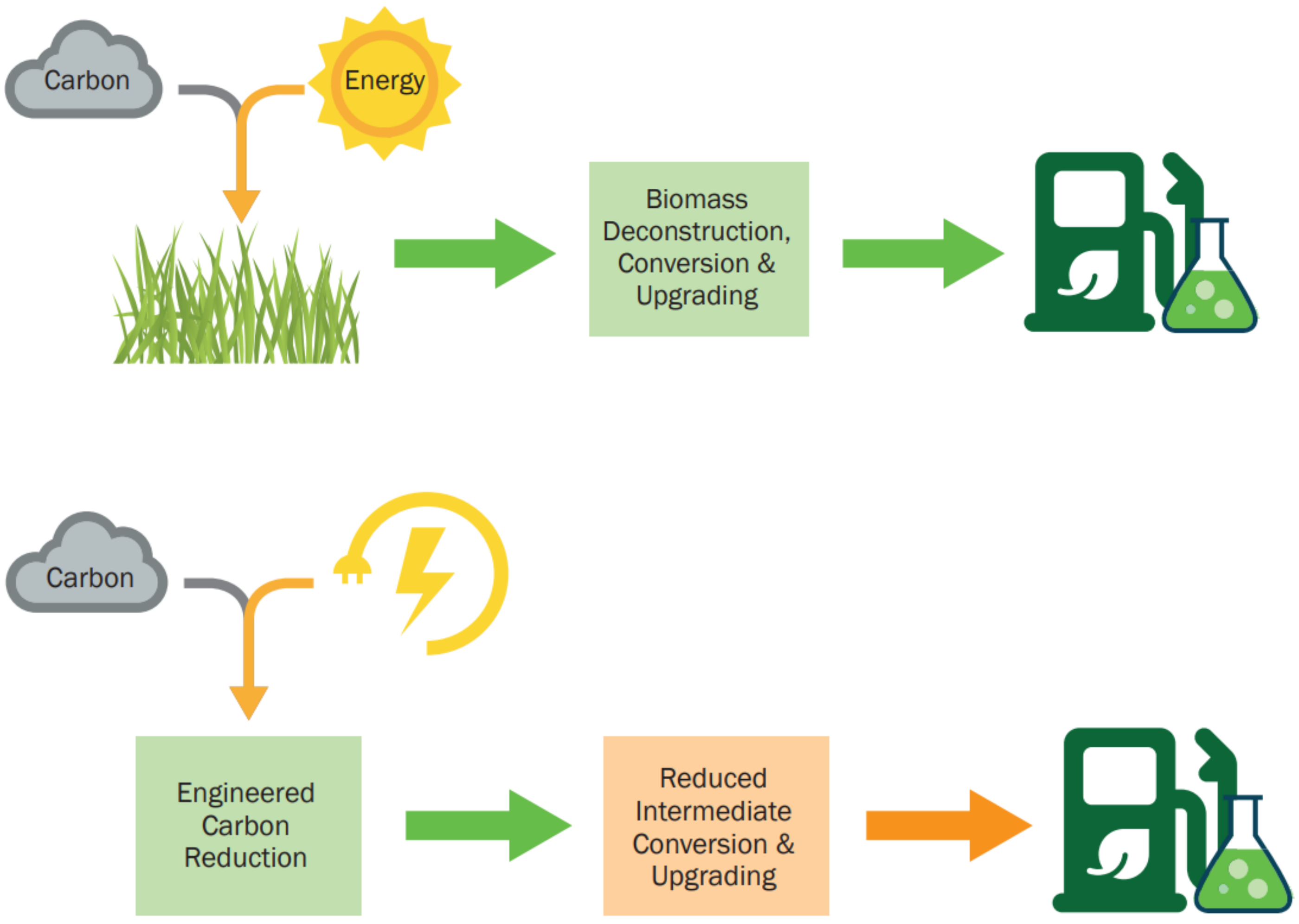
BETO Efforts in CO_2 Utilization



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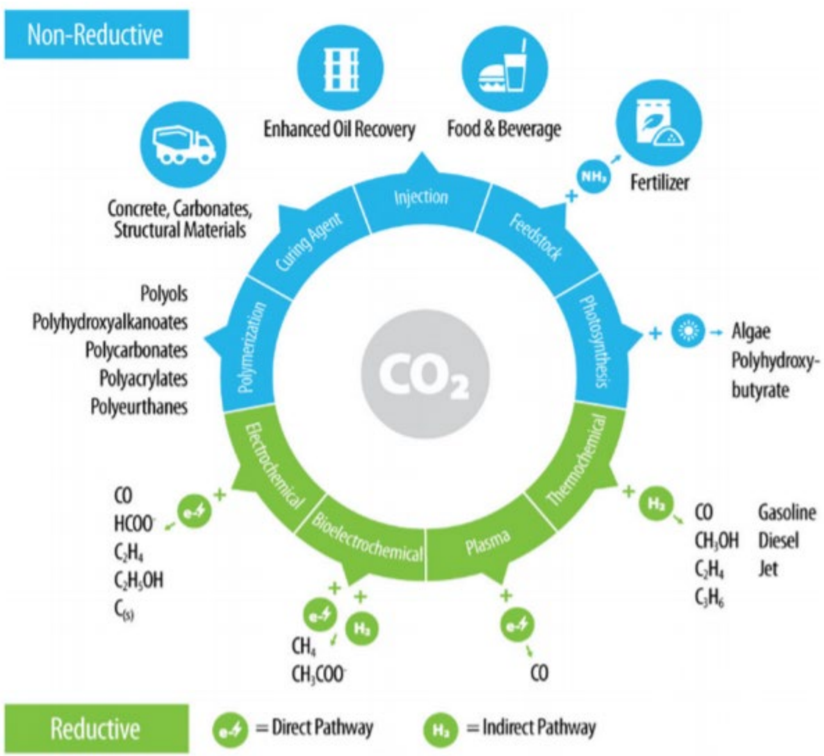
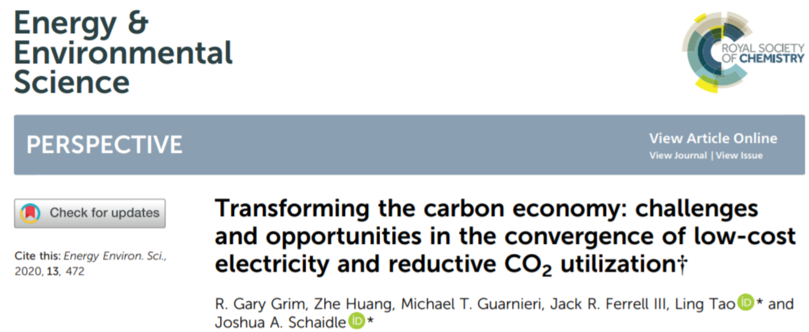
Current efforts in CO2U

Initiated a "Feasibility Study" outlining the current state of technology, markets and technical barriers to achieving commercial relevance




Energy & Environmental Science

PERSPECTIVE

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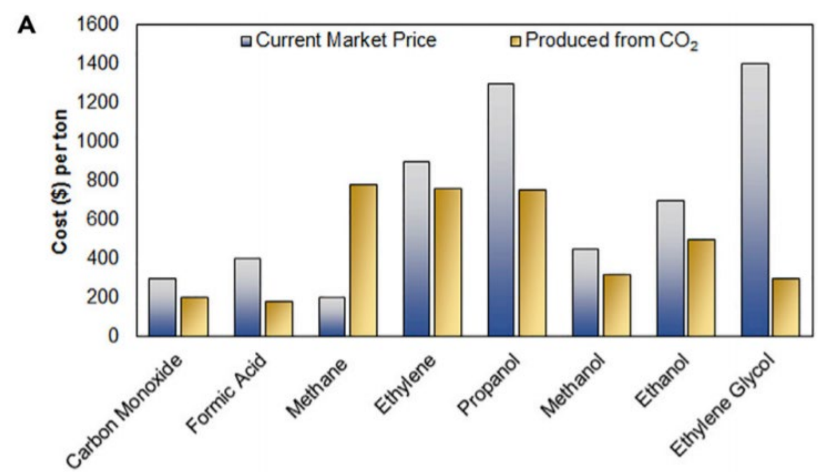
Cite this: *Energy Environ. Sci.*, 2020, 13, 472

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 *



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Current efforts in CO2U

	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

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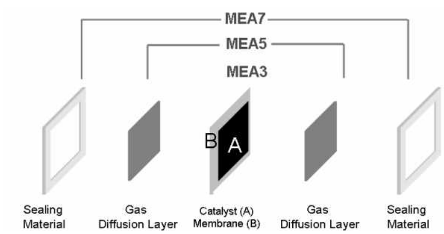
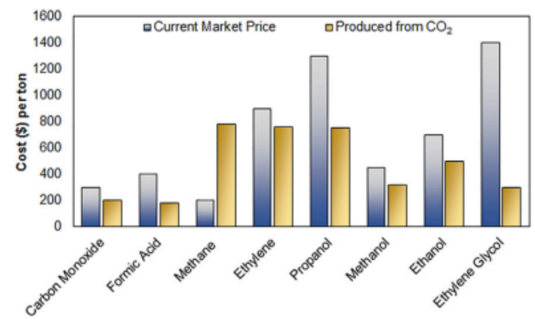
Current efforts in CO2U

CO_2 Electrocatalysis to produce intermediates

Enabling Studies:

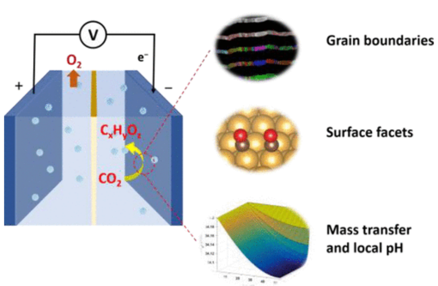


Determining the optimal design for electrocatalytic units



Determining the techno-economic viability of generating intermediates from CO_2

Electrocatalysis R&D:



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Johns Hopkins University

University of Delaware 1743

Dioxide Materials
The CO_2 Recycling Company

DNV·GL

SKYRE

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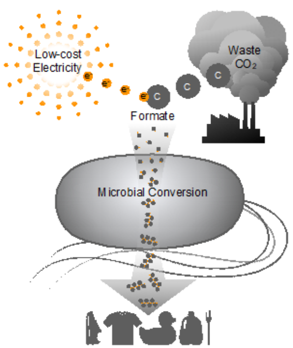
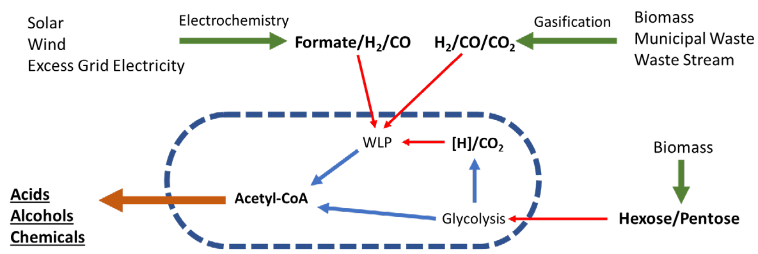
Current efforts in CO2U

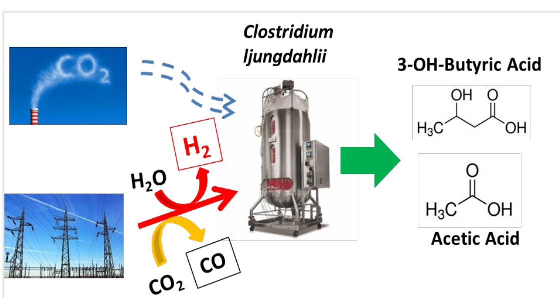
Upgrading of CO_2-derived intermediates

Engineering microorganisms to upgrade formate or methanol:





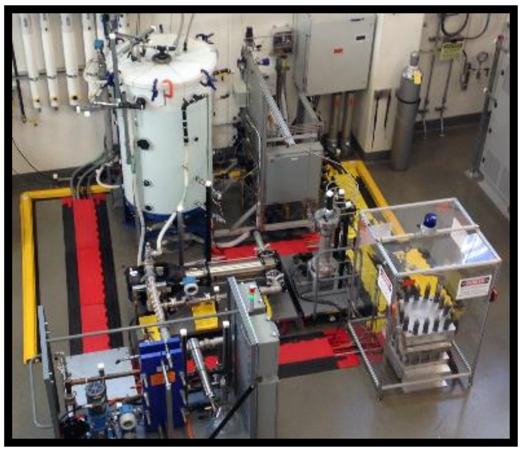
Engineering microorganisms to upgrade carbon monoxide:



Current efforts in CO2U

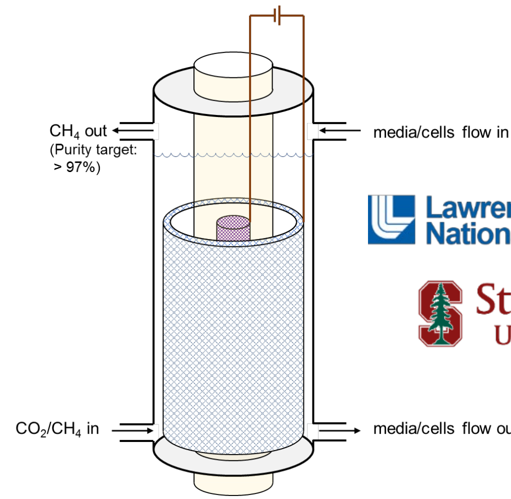
CO_2 conversion to methane for energy storage and improved use of biogas

NREL Electrolyzer System



SoCalGas

250 kW PEM electrolyzer and 700L bioreactor for the SoCal Gas work at NREL in collaboration with HFTO and BETO



Lawrence Livermore National Laboratory

Stanford University

DOE and SoCalGas funding LLNL and Stanford in new power-to-gas research: microbial electromethanogenesis

02 August 2018

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Interest in net-zero carbon fuels

ENERGY • SHELL

Shell becomes the largest global energy company to commit to a net-zero emissions goal by 2050

BY KATHERINE DUNN
April 16, 2020 11:07 AM EDT

Delta announces $1bn plan to be first carbon neutral airline

Airline is committing $1bn over next 10 years to mitigate all emissions from its global business

Climate and Environment

BP, one of the world's biggest oil-and-gas companies, says it is turning over a green leaf

419 views | Oct 15, 2020, 06:00am EDT

U.S. Utility Companies Rush To Declare Net-Zero Targets

Scott Carpenter Senior Contributor
Energy

Can the aviation industry really go carbon neutral by 2050?

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

Jonathan Shieber @jshieber / 12:30 pm EDT • September 19, 2019

Comment

Sep 21, 2020 - Energy & Environment

Walmart aims for zero greenhouse gas emissions by 2040

Ben Geman, author of Generate

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Net-Zero Carbon Fuels Tech Team

- **Scope**: Investigate options for generating liquid carbon-based fuels with a reduced carbon intensity (CI) such that, from a life cycle carbon accounting standpoint, they have a net carbon emissions profile approaching zero.

- **Objective**: Objective is to take an "LCA-first" approach to assessing potential renewable fuel pathways, where the technology is optimized for reduced carbon intensity and the technoeconomics of these pathways are assessed to determine the associated cost of carbon mitigation for a given technology solution set.

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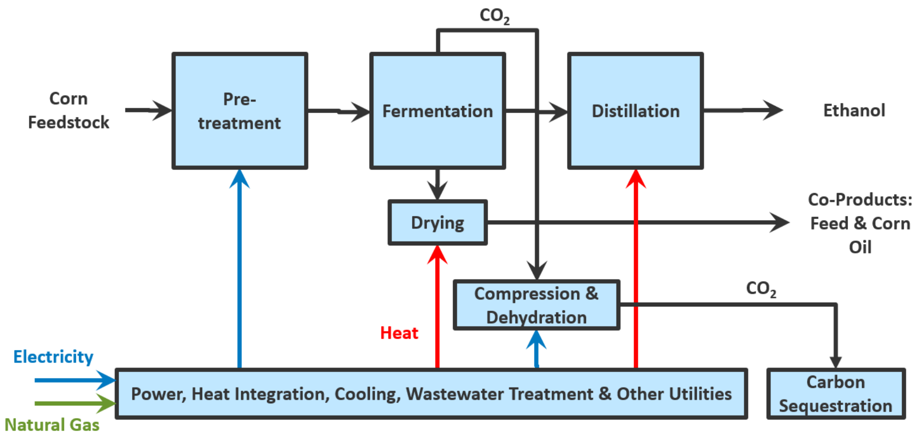
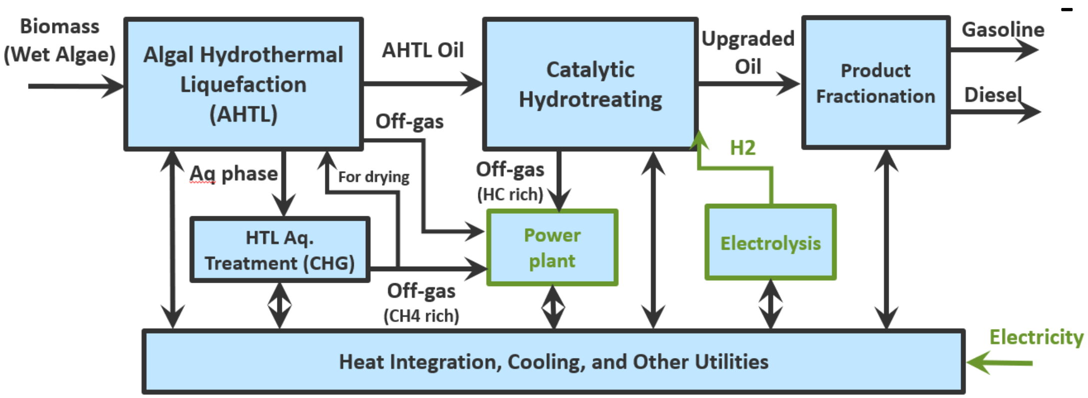
Initial Net-Zero Tech Team Analyses

1. Corn starch to ethanol, w/CCS



- Leverage existing carbon drawdown analyses
- Expand to various feedstocks
- Expand CCS within pathway
- Substitute fossil energy inputs for increasing renewables on the grid

2. Algae-to-hydrocarbons



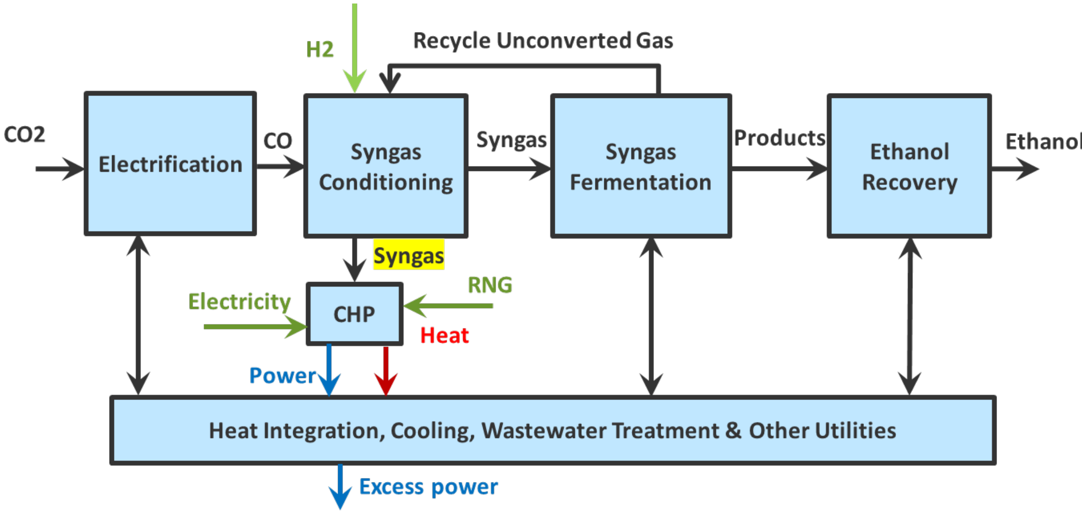
- Leverage existing algae analyses
- Can be used to compare photosynthetic vs non-photosynthetic solutions

Can integrate renewable H_2 into hydrotreating

Further integration of electricity

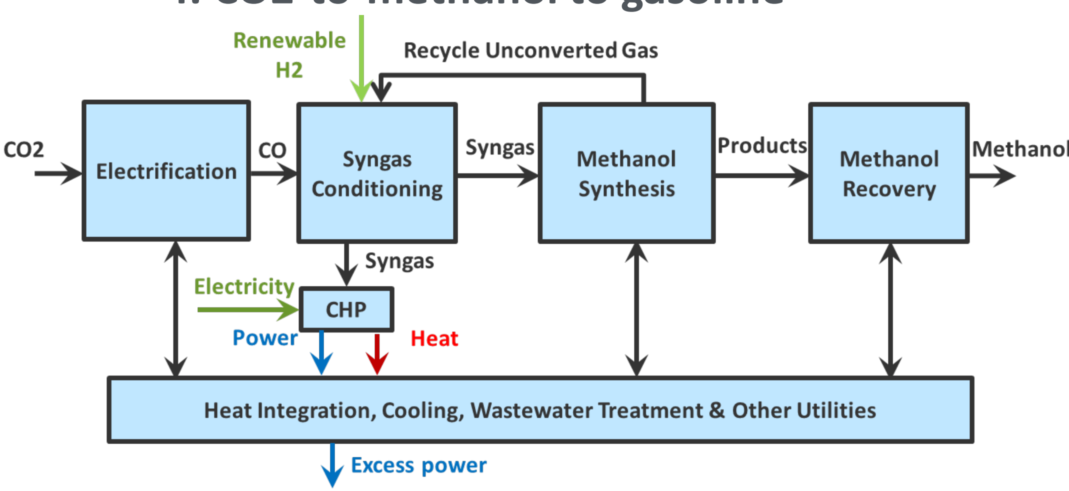
Initial Net-Zero Tech Team Analyses

3. CO2-to-CO to jet fuel



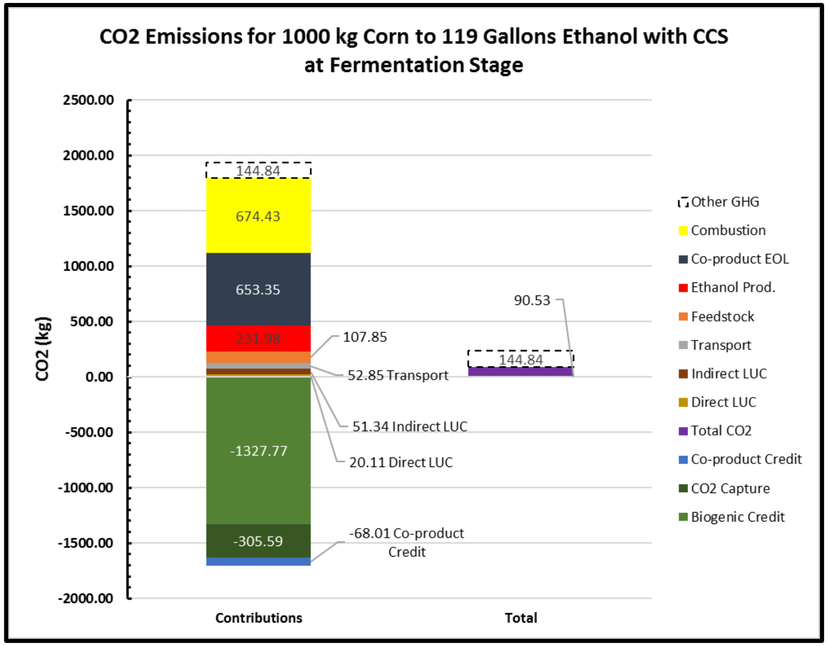
- Leverage existing biomass syngas fermentation literature
- Compare reverse water-gas shift to electrocatalysis for obtaining syngas
- Examine H_2 generation + Oxy-gasification of biomass
- Compare to common FT fuel routes

4. CO2-to-methanol to gasoline



- Leverage existing biomass gasification literature and FE work
- Vary H_2 source (SMR vs SMR+CCS vs H_2O)
- Thermocat vs electrocat.
- MeOH as a product or intermediate
- Haldor Topsoe's TIGAS Process

Initial findings: Corn EtOH + CCS



Although this pathway is not net carbon-negative, we have shown that the Ethanol with Fermentation CCS case delivers an 81.6% decrease in product-specific CO2 emissions when compared to the traditional fossil-fuel pathway (gasoline).

Average corn ethanol today: ~40% reduction.

Minimum Ethanol Selling Price: $1.77/gal

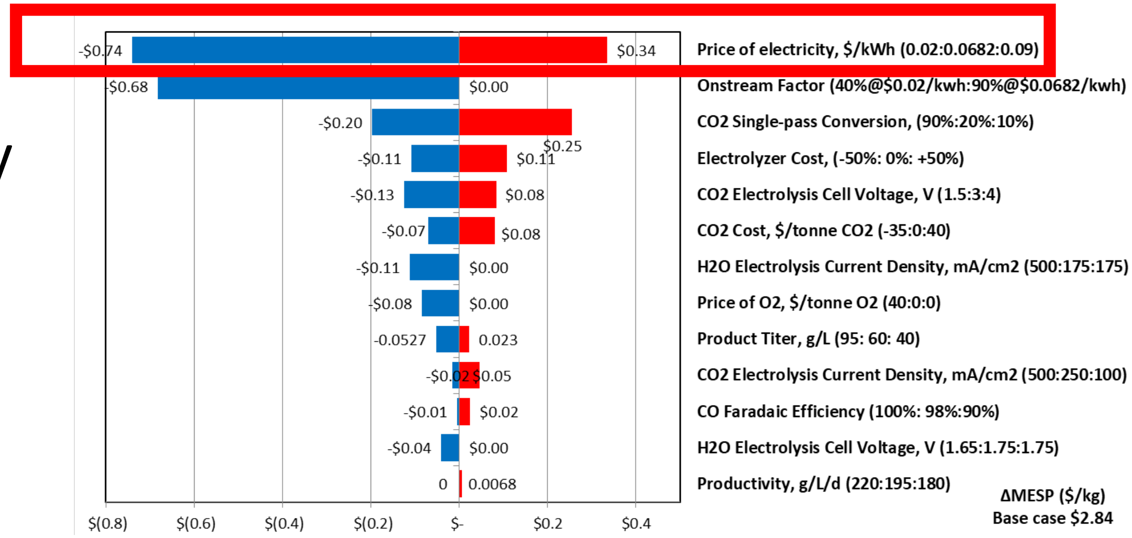
Minimum Ethanol Selling Price w/CCS: $1.92/gal

This additional $0.14 per gallon price ends up being about **$40/ton CO_2**

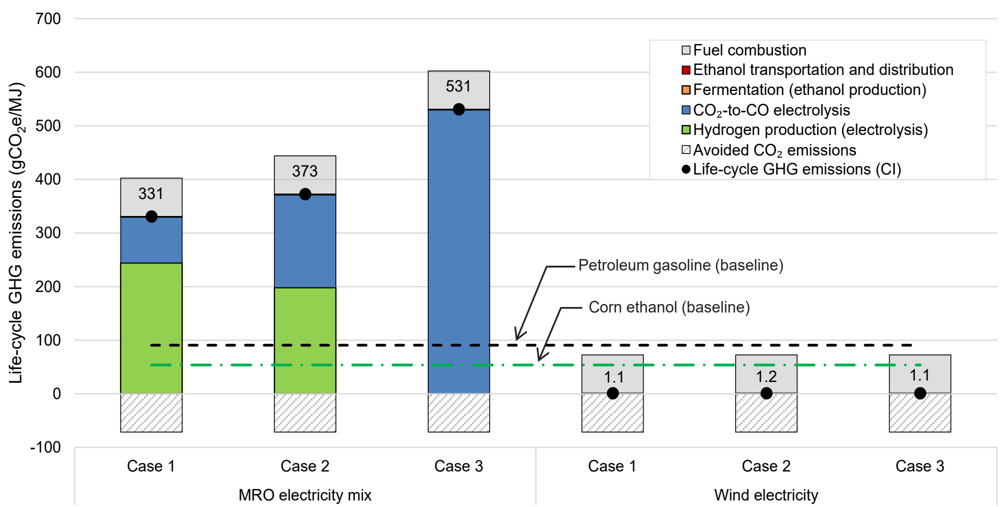
(45Q tax credit = $50/ton)

Initial findings: Fuels via CO2 Electrocatalysis (“E-fuels”)

Price of electricity is the key factor in TEA



Carbon intensity of the electricity is the key factor in LCA



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Net-Zero Carbon Fuels vs “e-fuels”

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

Contact

Ian Rowe, Ph.D.

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