Renewable Energy Enabled Carbon Optimized Bioconversion

David M. Babson, Ph.D.
Program Director
Advanced Research Projects Agency – Energy
U.S. Department of Energy

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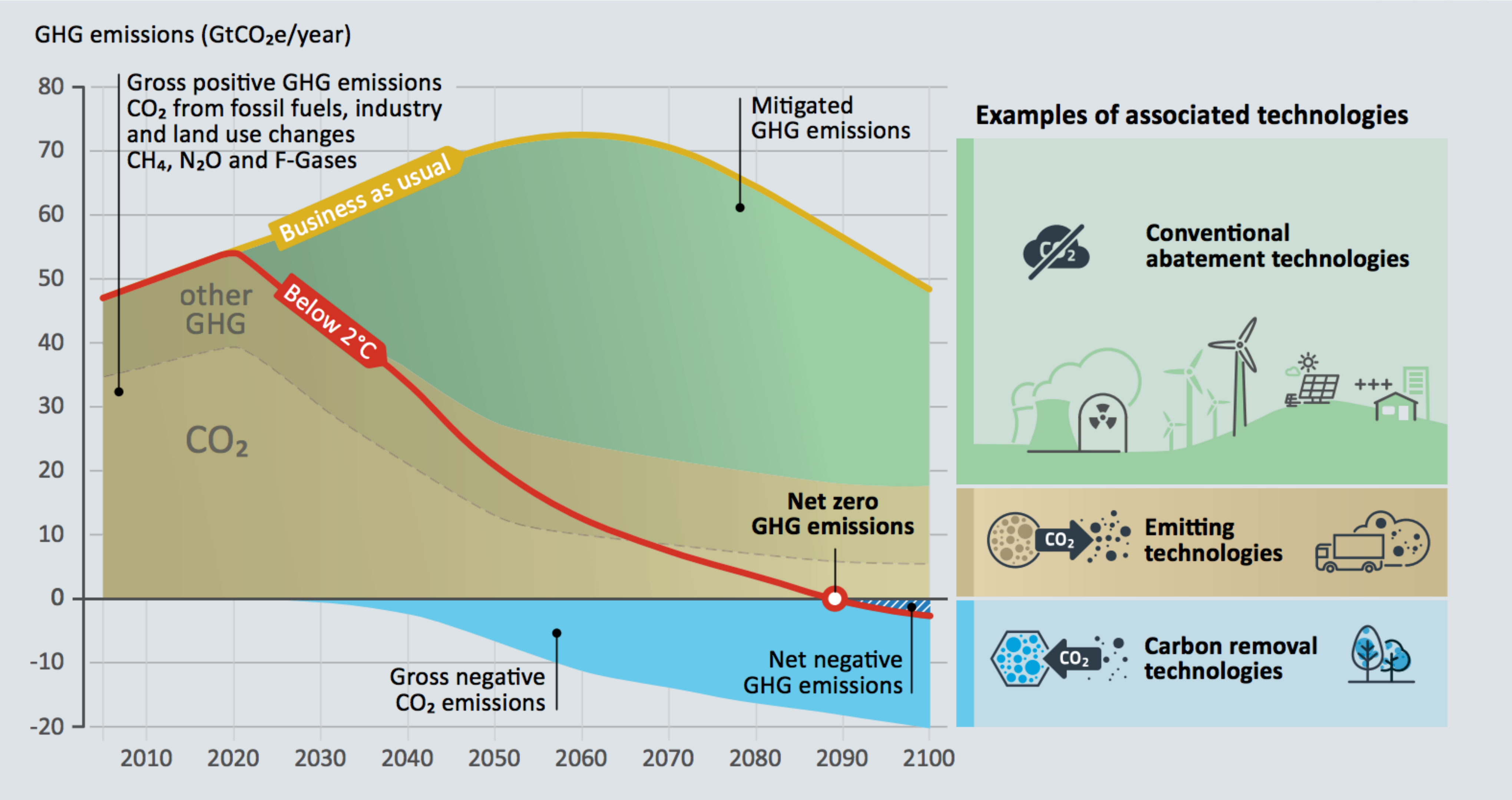
September 26, 2019

All paths to 2⁰ C go through zero



National Academy of Sciences. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* 2019. p. 3

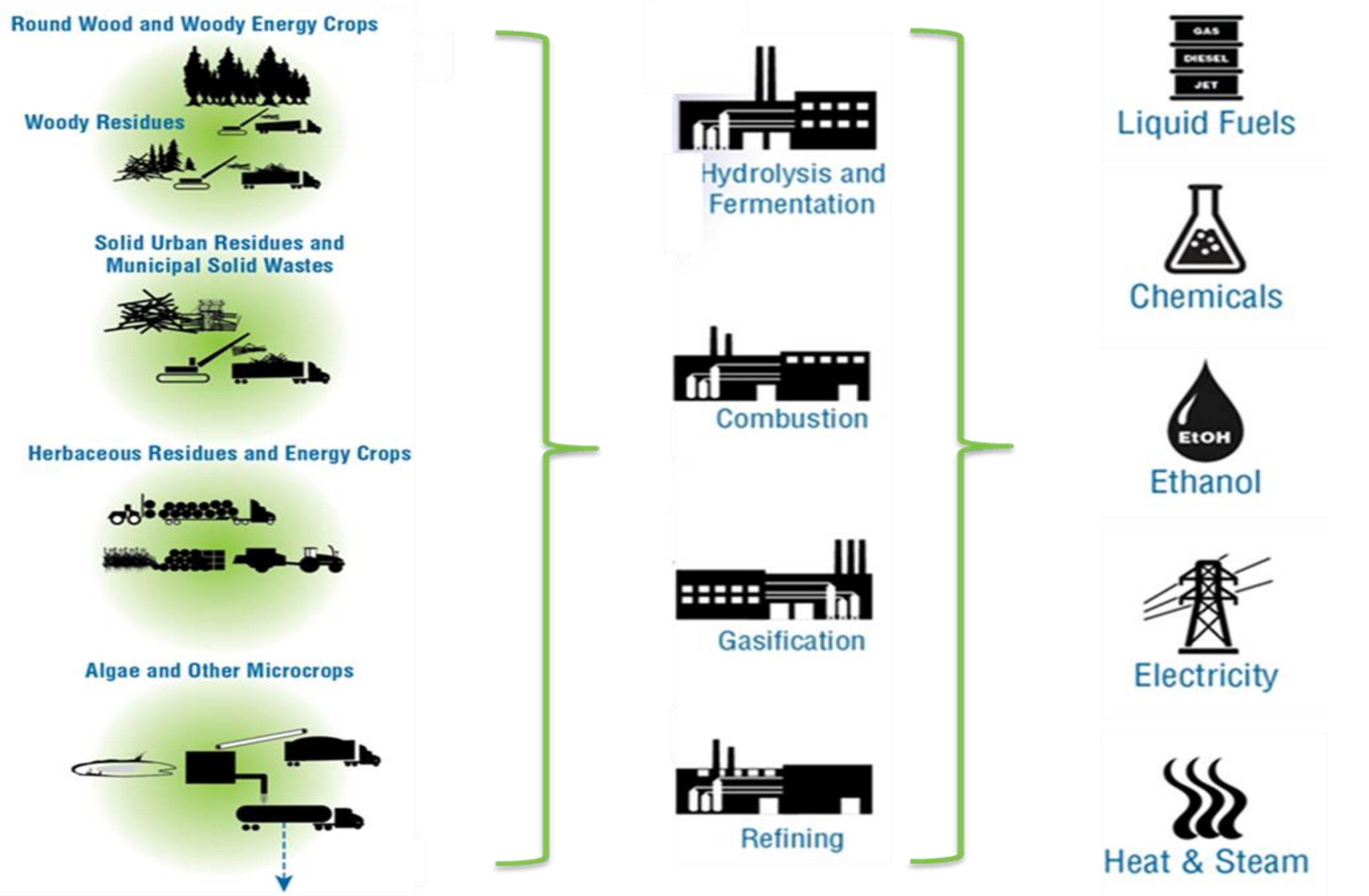
A carbon-conscious economy is not a *low-carbon economy* as much as it will be a *renewable "new" carbon economy*

The low carbon economy incentivizes carbon reduction

The new carbon economy will incentivizes carbon optimization

The bioeconomy concept

Feedstock | Conversion | Products



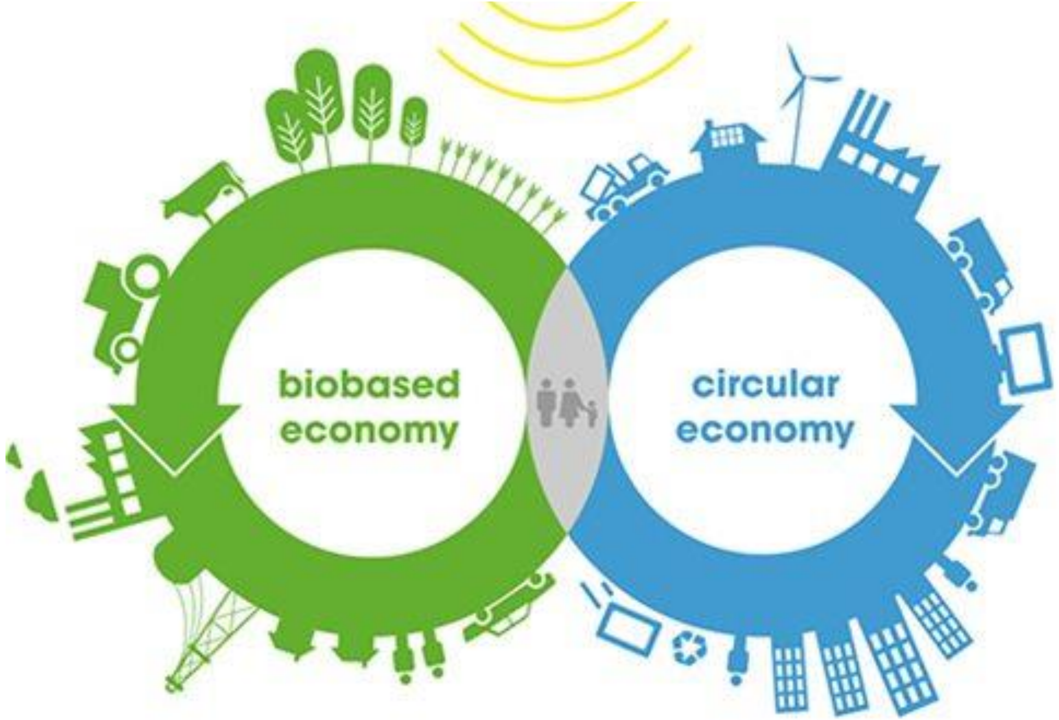
- **Revenue and economic growth**
- **Broad spectrum of new jobs**
- **Rural development**
- **Advanced technologies and manufacturing**
- **Reduced emissions and Environmental Sustainability**
- **Export potential of technology and products**
- **Positive societal changes**
- **Investments and new infrastructure**

Manage carbon in the economy

Manage carbon to get it out of the economy

The new carbon economy refers to a prosperous, growing economy that captures and stores more carbon than it emits

Managing carbon in the economy
Circular new carbon strategies



Managing to get carbon out of the economy
Negative Emission Technologies (NETs)

Biological NETs

Engineered NETs

Hybrid NETs

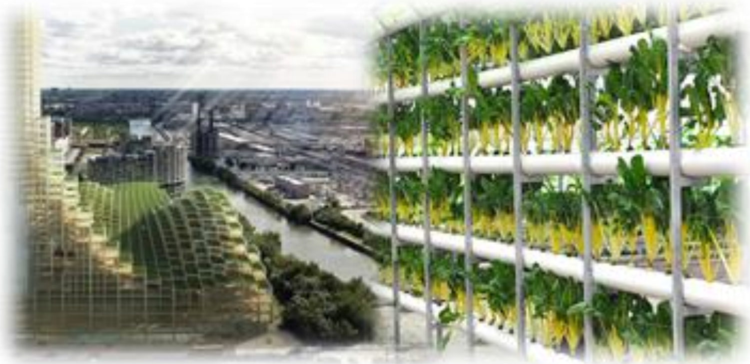
Environmental Drivers for Innovation

Carbon / GHG Emissions	Land
	

Our global economy needs to be structured in a way that incentivizes not only land and carbon 'neutrality', but promotes becoming both carbon and land negative. In this environment the bioeconomy wins.

Implement numerous strategies to reduce emissions and spare land

GHG emissions and land sparing strategies must be widely and simultaneously deployed



Vertical Agriculture & Engineered Ecosystems

Landscape Design & Agroecology

Living fertilizers for agriculture systems

Carbon Utilization and Removal

Precision Agriculture

Food – What and How

ARPAe before me: TERRA - ROOTS Program Vision

THE CONVERGENCE OF BIOLOGY, ENGINEERING AND COMPUTER SCIENCE TO ACCELERATE BREEDING GAIN

***T**ransportation*
***E**nergy*
***R**esources from*
***R**enewable*
***A**griculture*

Increased
Phenotyping +
Data Analytics
=
Increased
Genetic Gain

Crop Genetic Gain

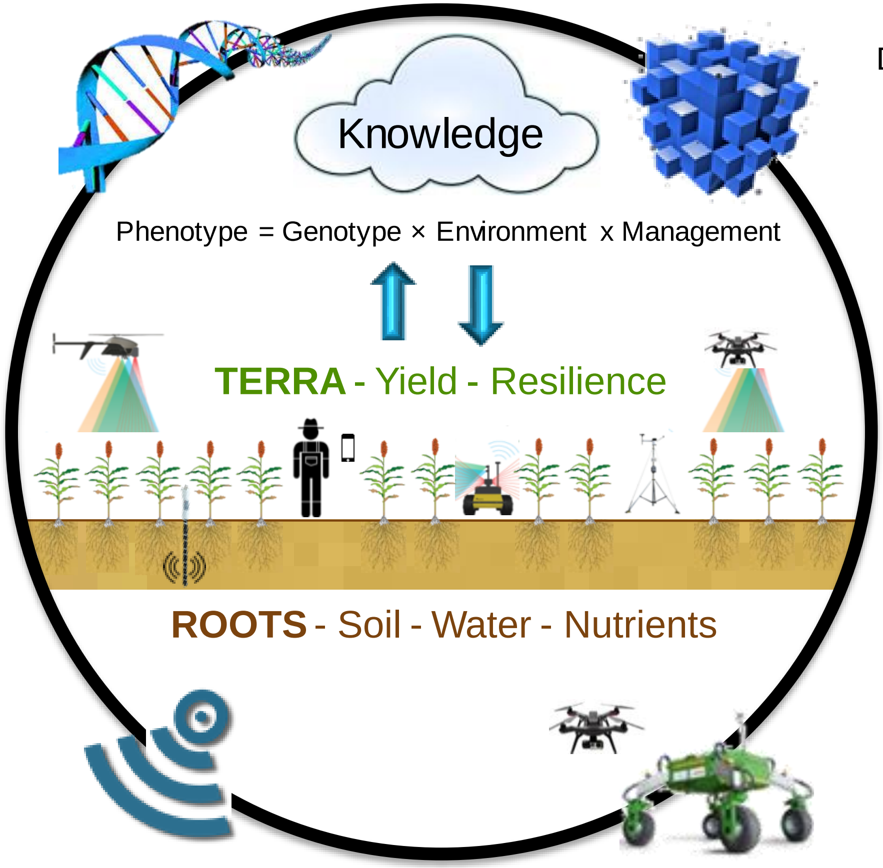
Genetics
Molecular Biology

Gene and Trait Associations

Agriculture
Physiology and Agronomy

High Resolution Phenotypes

Sensors
Abiotic and Biotic



High Throughput Field Data Acquisition

Data
Distributed and Secure

Crop Prediction Algorithms

Analytics
Computational Pipelines

AI Systems Machine Learning

Robotics
Scalable and Reliable

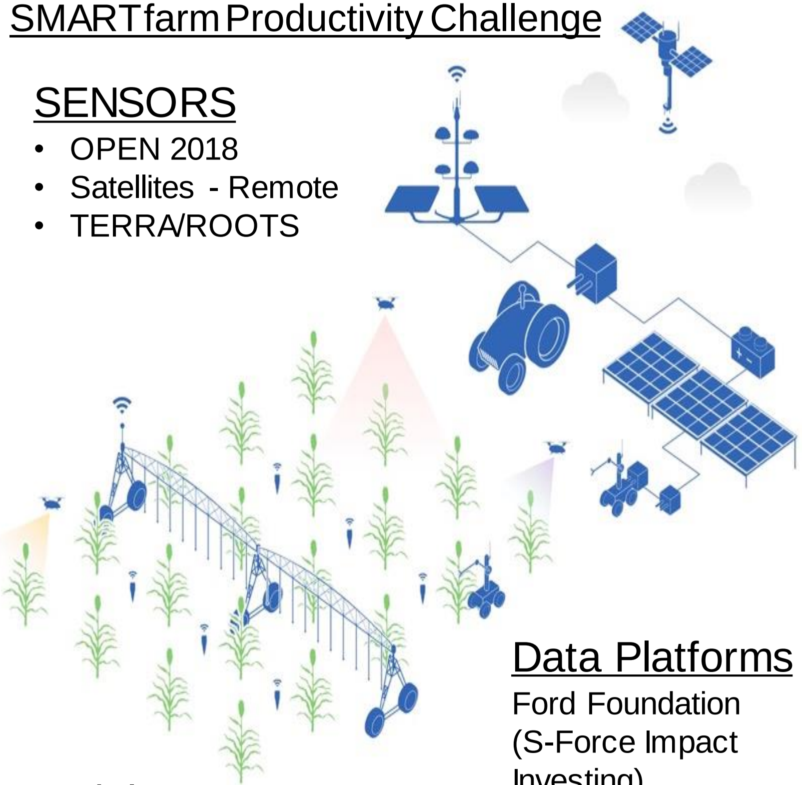
***R**hizosphere*
***O**bservations*
***O**ptimizing*
***T**errestrial*
***S**equestration*

Tools to improve crop nutrient utilization and carbon sequestration

Potential New ARPAe Programs and Challenges

DIGITAL AGRICULTURE, CARBON MANAGEMENT, AND CARBON REMOVAL

SMARTfarm Productivity Challenge



SENSORS

- OPEN 2018
- Satellites - Remote
- TERRA/ROOTS

Data Platforms

Ford Foundation (S-Force Impact Investing)

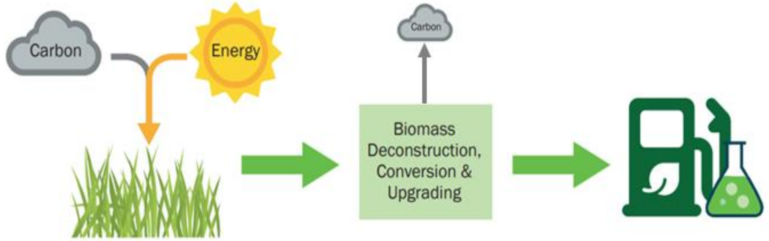
Models

- GREET® (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model)
- DNDC (DeNitrification-DeComposition Agroecosystem Model)

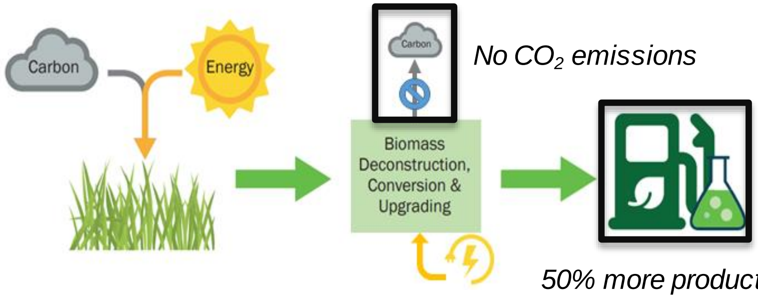
ENERGY CARBON OPTIMIZED SYNTHESIS FOR THE BIOECONOMY (*ECOSynBio*)

Leveraging low-carbon power for carbon-optimized biorefining

Traditional fermentation

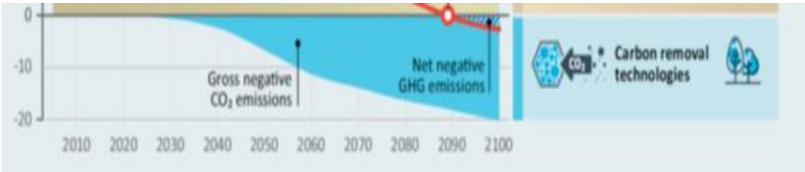


ECO-fermentation



Enabling 100% carbon efficient conversion

NEGATIVE EMISSIONS ADVANCED TECHNOLOGIES (*NEAT*)



Biological Solutions

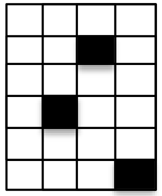
Engineered Solutions

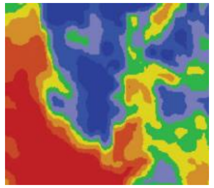
Hybrid Solutions

Developing technologies to enable inexpensive and energy efficient carbon removal

Processors are looking for ***supply-chain wide*** solutions to lower the carbon intensity of their products

TERRA
Crops × Bots × Bytes
ROOTS





Crop Breeding

G x E

TERRA & ROOTS programs leverage data to identify the best genetics for biofuel productivity

Feedstock Production

G x E x M

Data capture in commercial production settings is too costly; value proposition is unclear.

Downstream Processing

G x E x M x P

Limited upstream visibility presents a barrier to paying a premium for sustainable feedstocks.

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CHANGING WHAT'S POSSIBLE

Genetics x Environment x Management x Processing

Processors are looking for ***supply-chain wide*** solutions to lower the carbon intensity of their products

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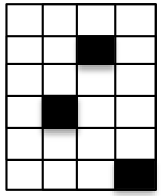

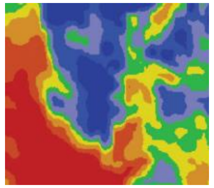

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Genetics x Environment x Management x Processing

Managing Carbon In the Economy: Energy Carbon Optimized Synthesis for the Bioeconomy (ECOSynBio)

‘Power-up’: Electrification Futures

Explore the potential to reduce U.S. greenhouse gas emissions through end-use electrification and power sector decarbonization.

The path to power sector decarbonization is somewhat clear, and many areas are amenable to electrification.

But what about those that are not amenable to electrification?

‘Power-up’: Electrification Futures

Explore the potential to reduce U.S. greenhouse gas emissions through end-use electrification and power sector decarbonization.

Power Sector

Carbon Based Fuel Requirements

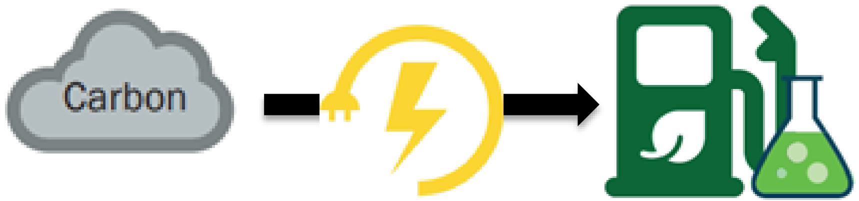
Can the world make the chemicals it needs without oil?

"Giving up [fossil] fuels doesn't involve chemical magic. Key industrial chemicals such as carbon monoxide (CO) and ethylene can already be made by adding electrons to abundant starting materials such as CO_2 and water, **<u>if efficiency is no object</u>**. The trick is to do so economically."

Service, R. Science. 19 September 2019

Biofuels

Electrofuels



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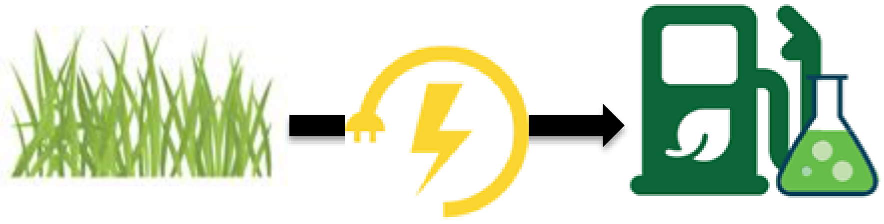
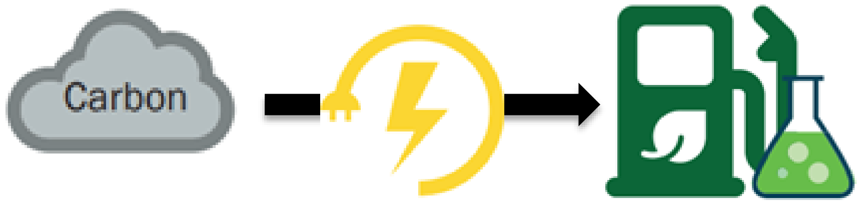
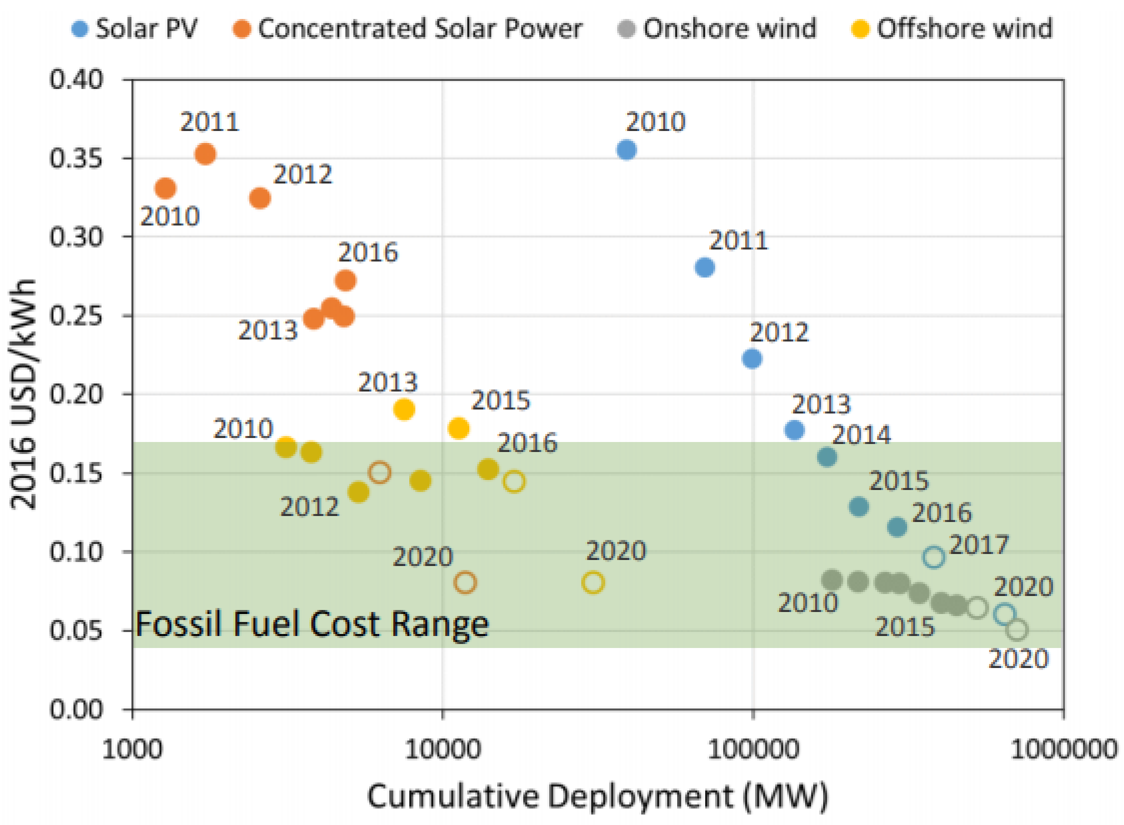
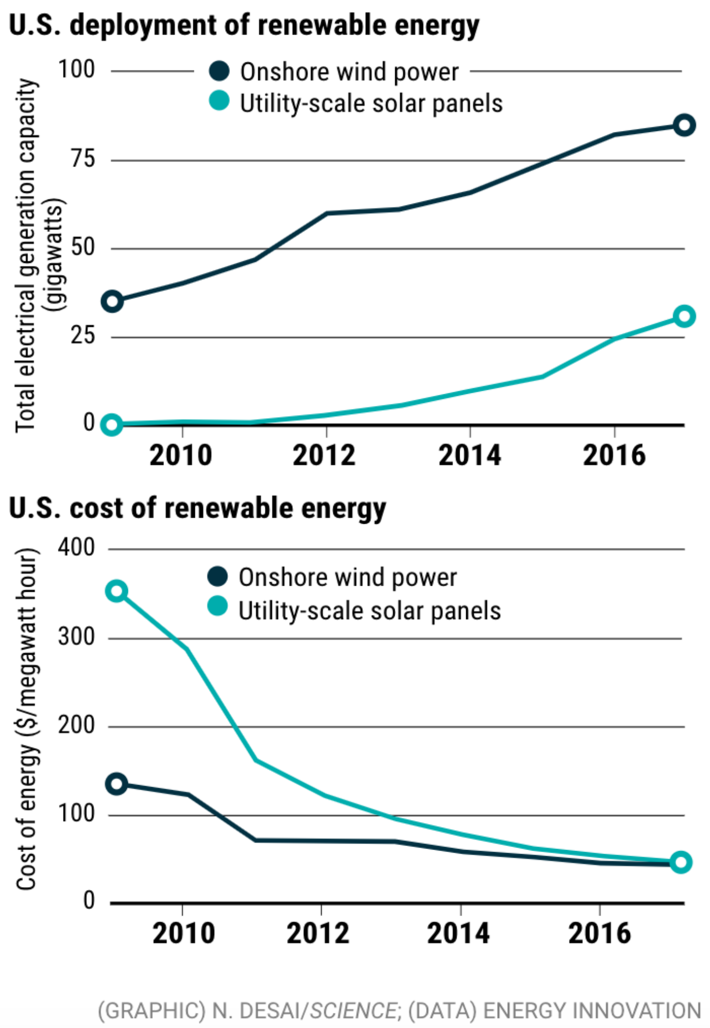


Electrofuels



Relevant trends in power and carbon





- The world's fifth-largest economy, California, has committed to 100% carbon-free power by 2045
- The price (direct or indirect) of emitting CO_2 will go up
- The price of and C-intensity of electricity will decrease

IRENA, Renewable Power Generation Costs in 2017

New carbon economy – not like the old one

Transition from vertical to horizontal integration

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Avoiding (completely) carbon waste during bioconversion

New working assumption: Power is inexpensive and low carbon

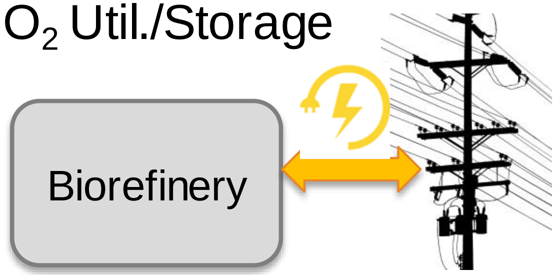
New paradigm for biorefining: Systems are 100% carbon efficient

Biorefining could be optimized in a number of ways to achieve these ends

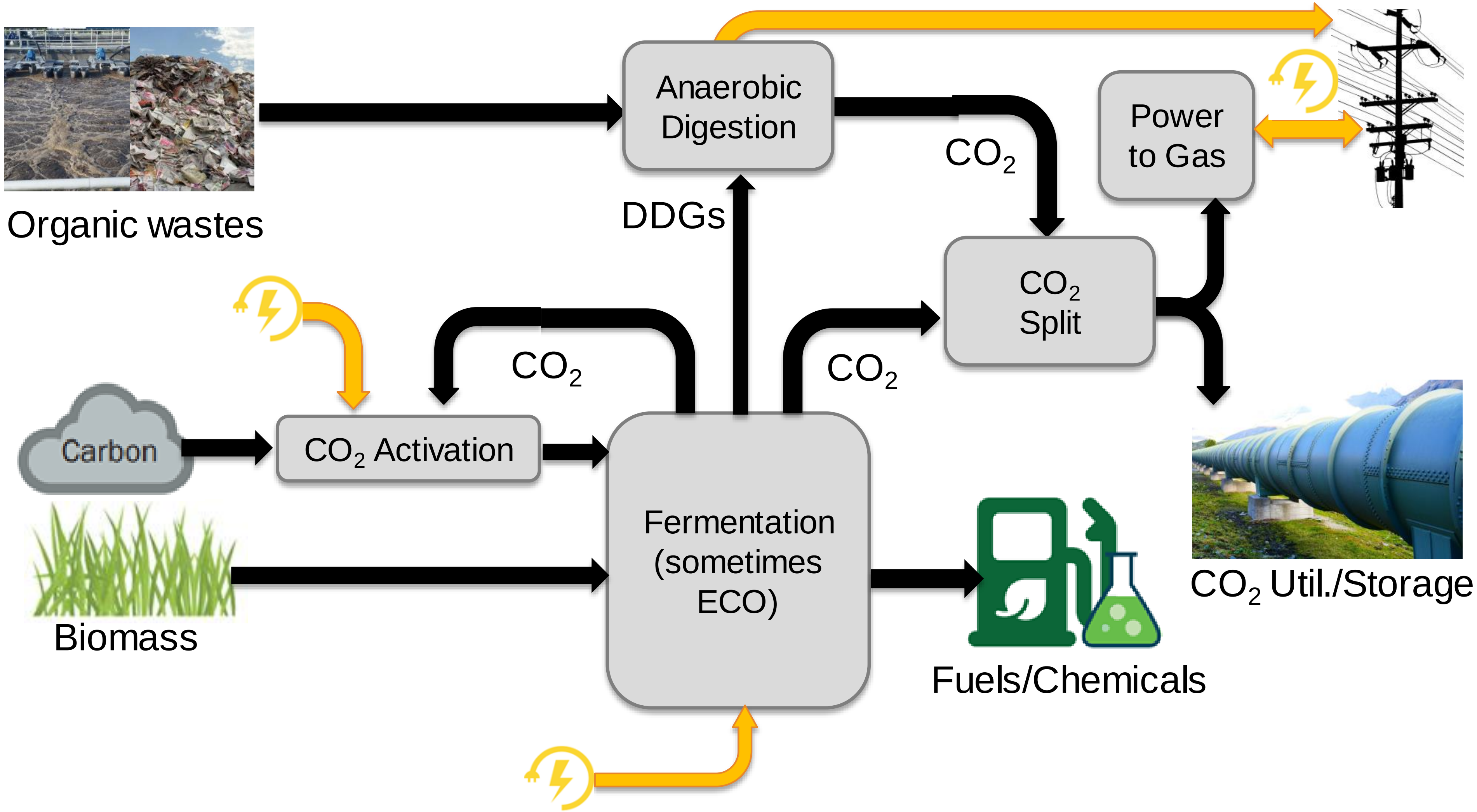
- Products
- Energy system integration
- Carbon storage
- Others or dynamic combinations

Fuels/Chemicals

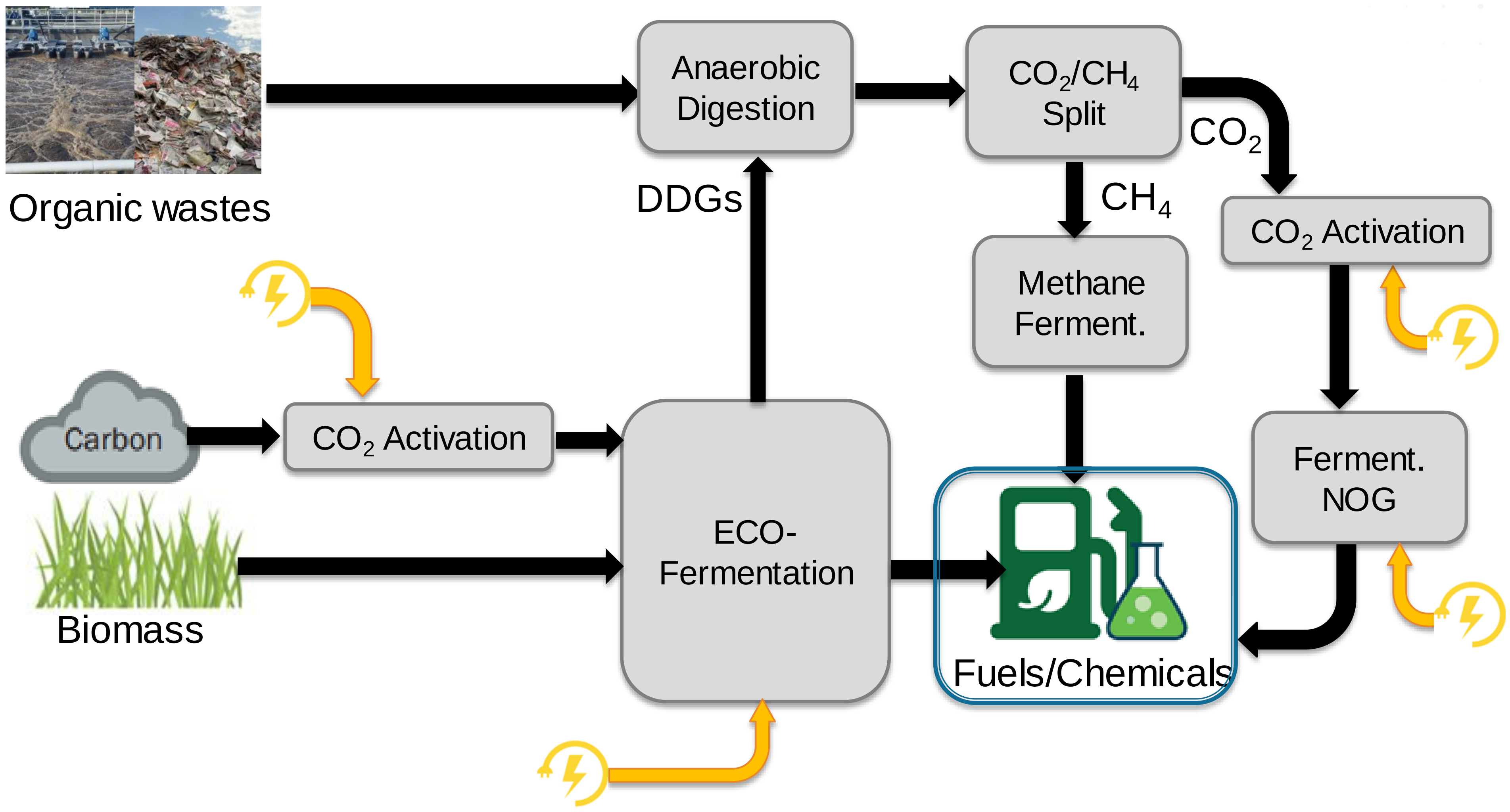
CO_2 Util./Storage



Designing energy-carbon optimized bioconversion systems



System optimized for fuel/chemical products



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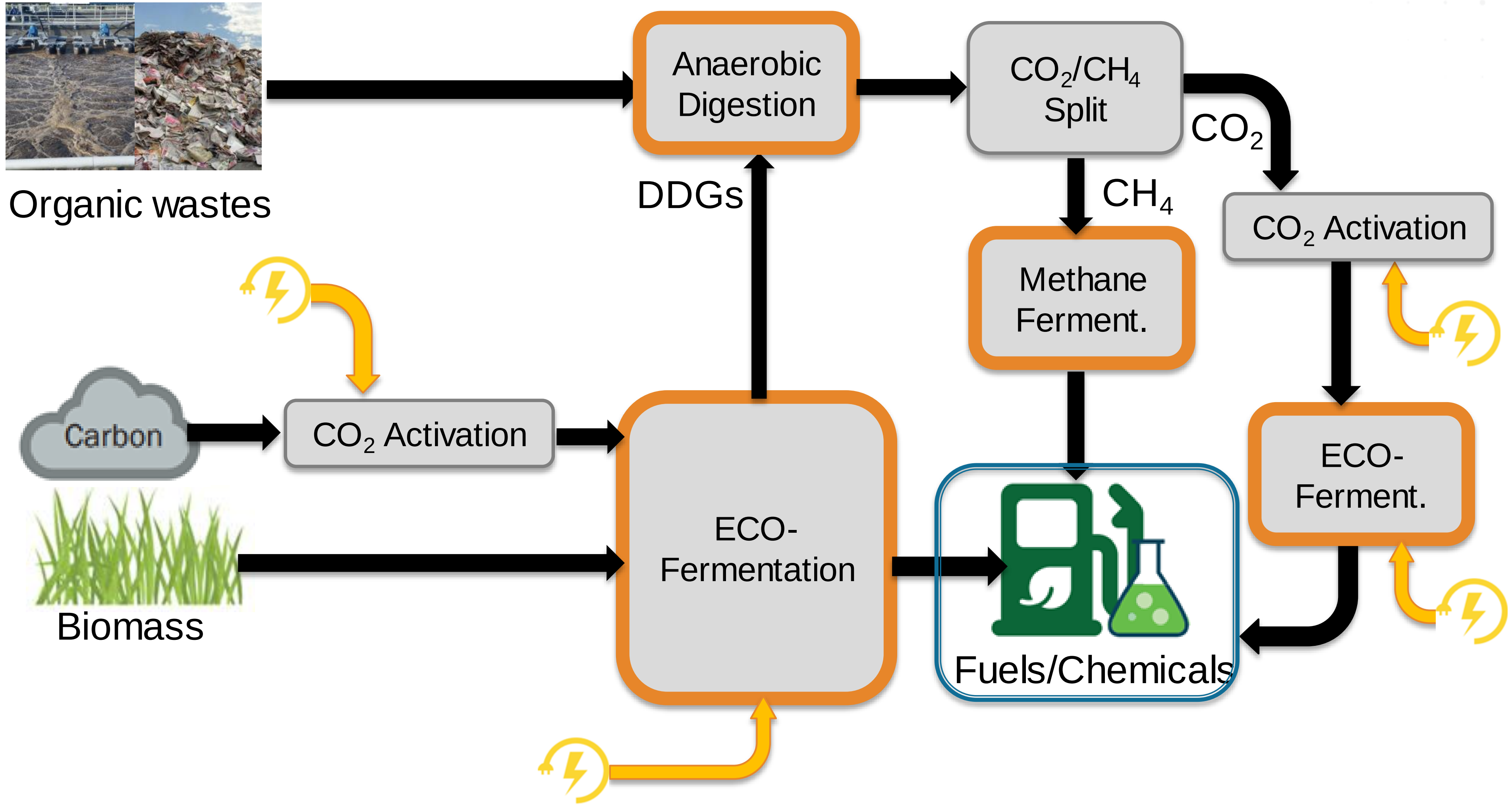
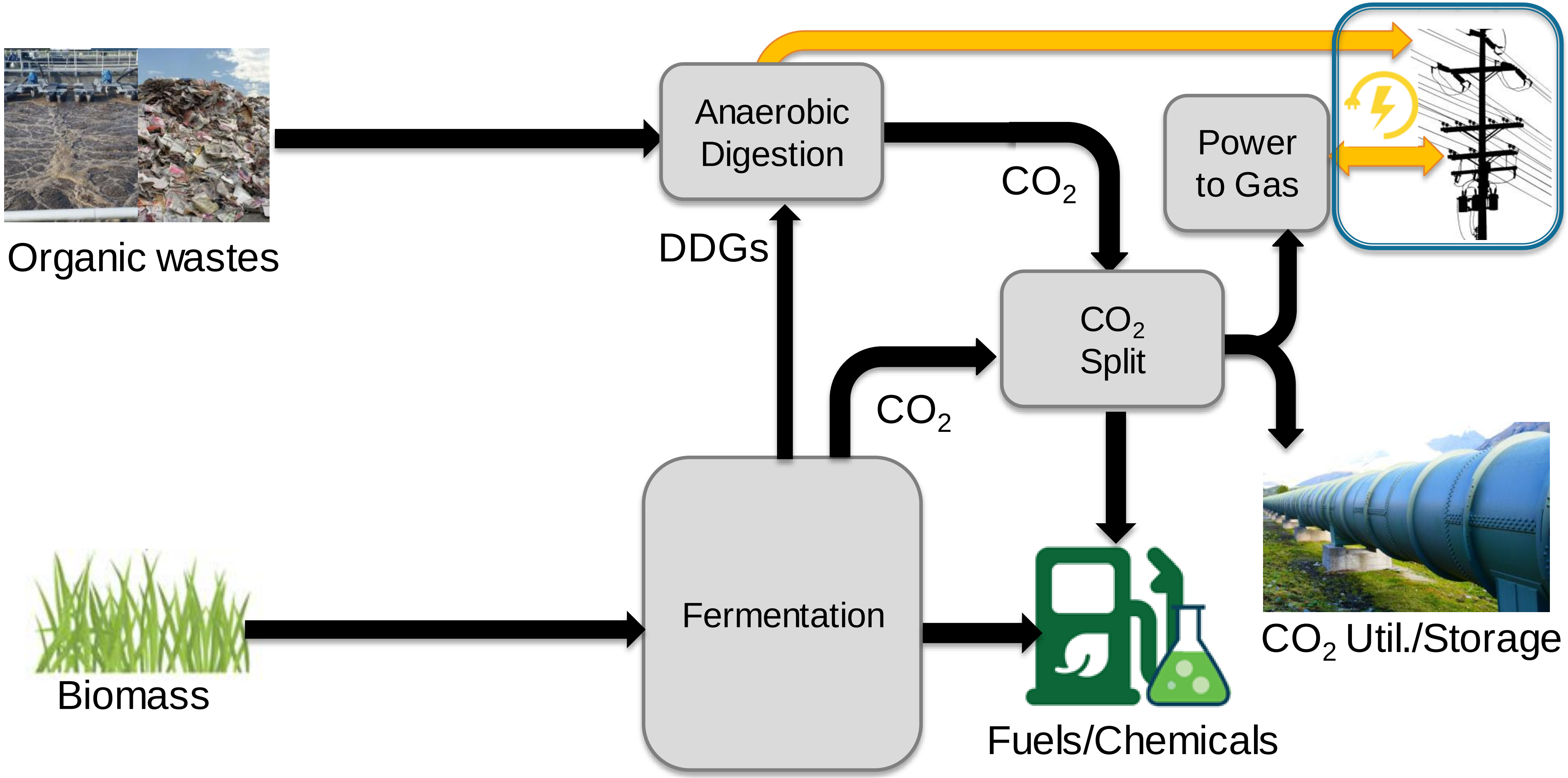


Unit processes to study

System optimized for grid integration and energy storage flexibility



CHANGING WHAT'S POSSIBLE

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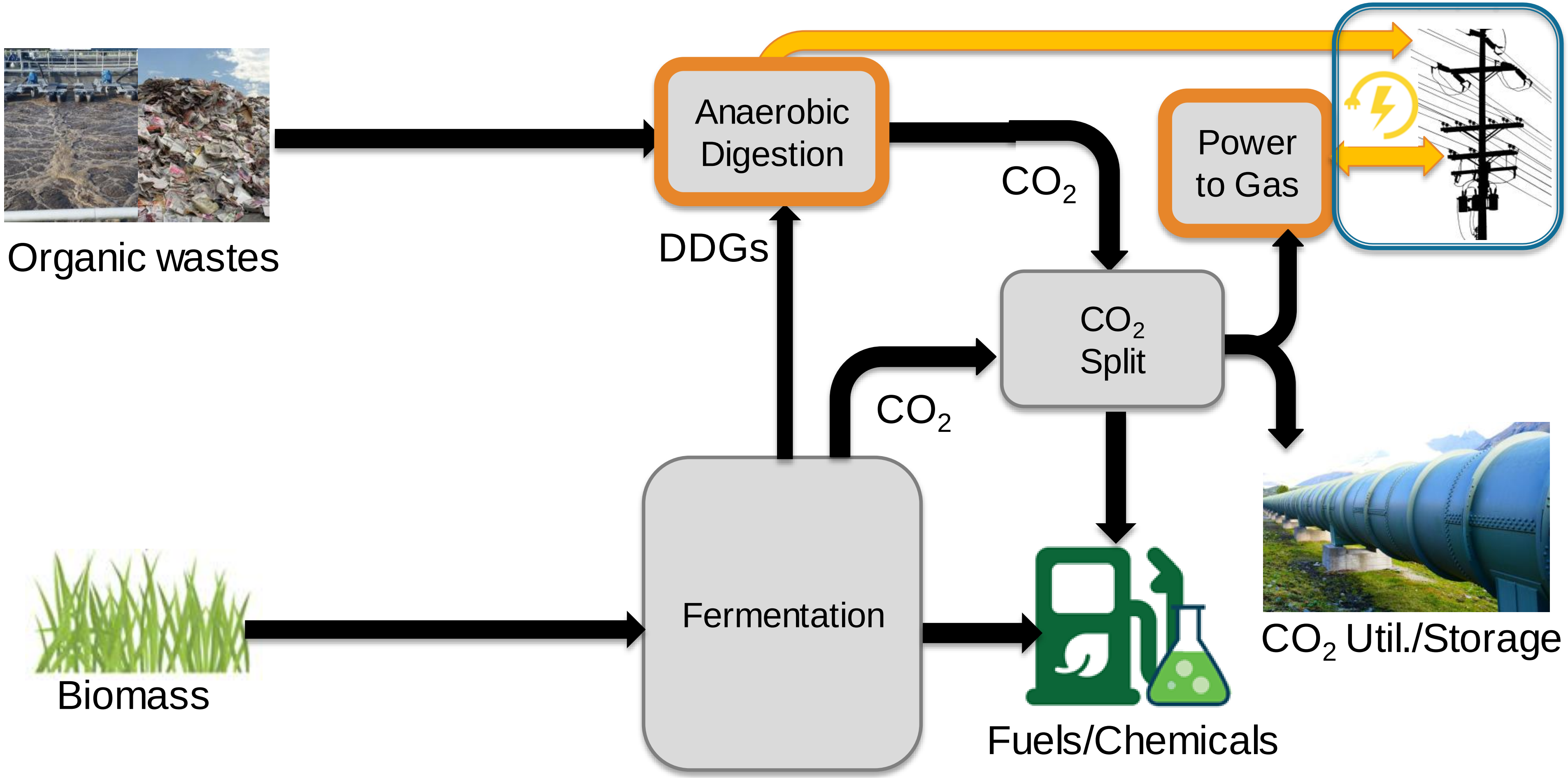
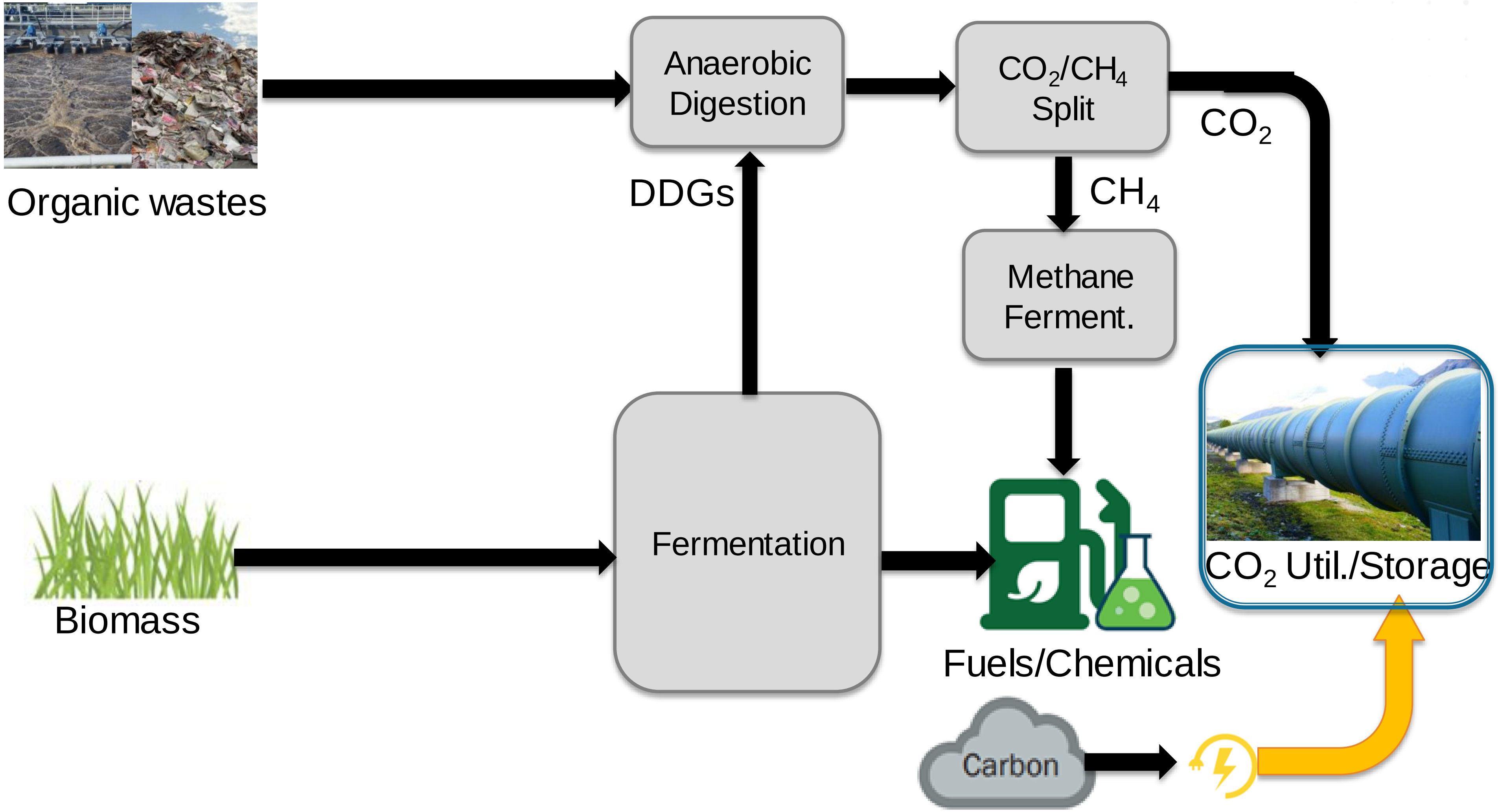


Unit processes to study

System optimized for carbon removal (BECCS)



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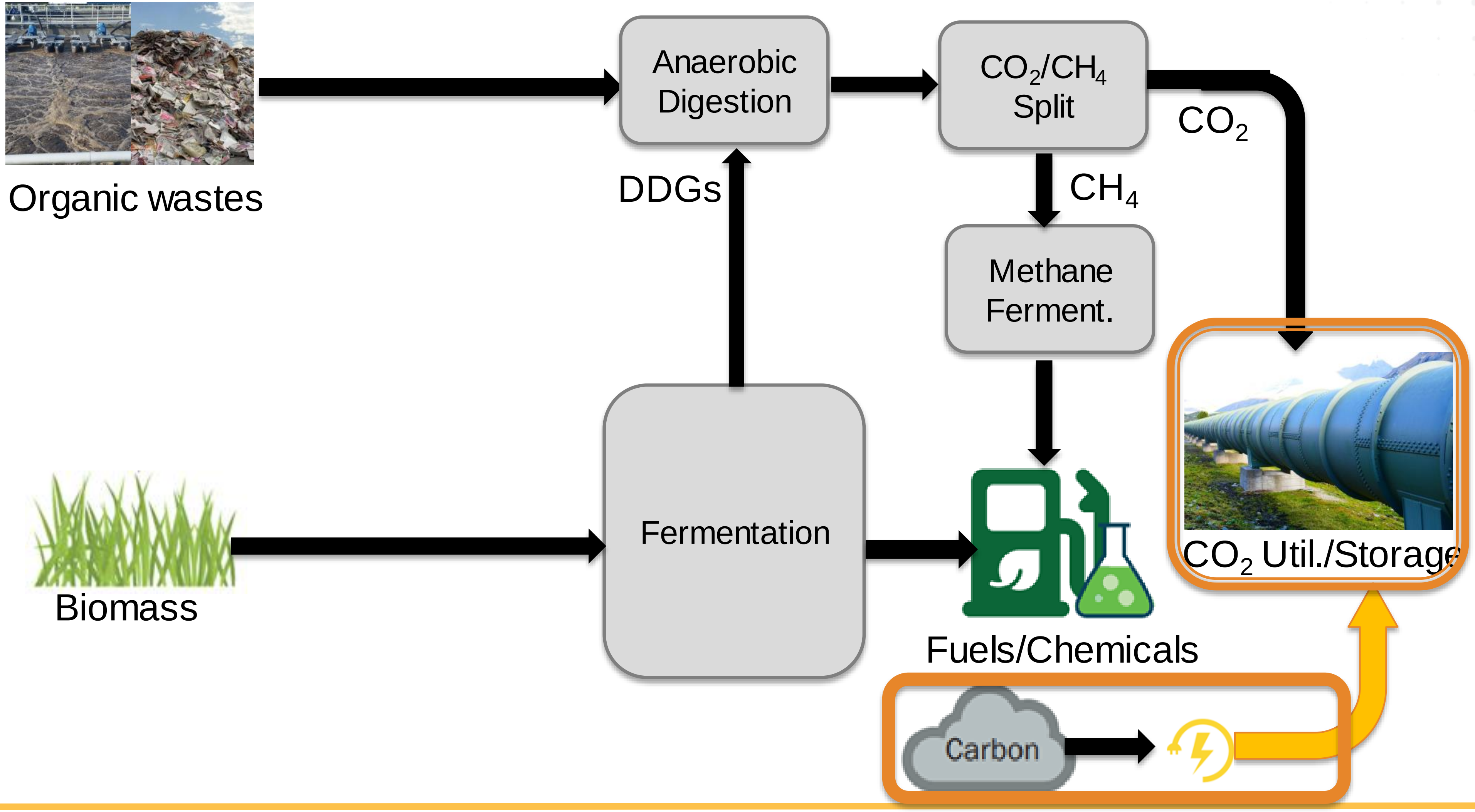
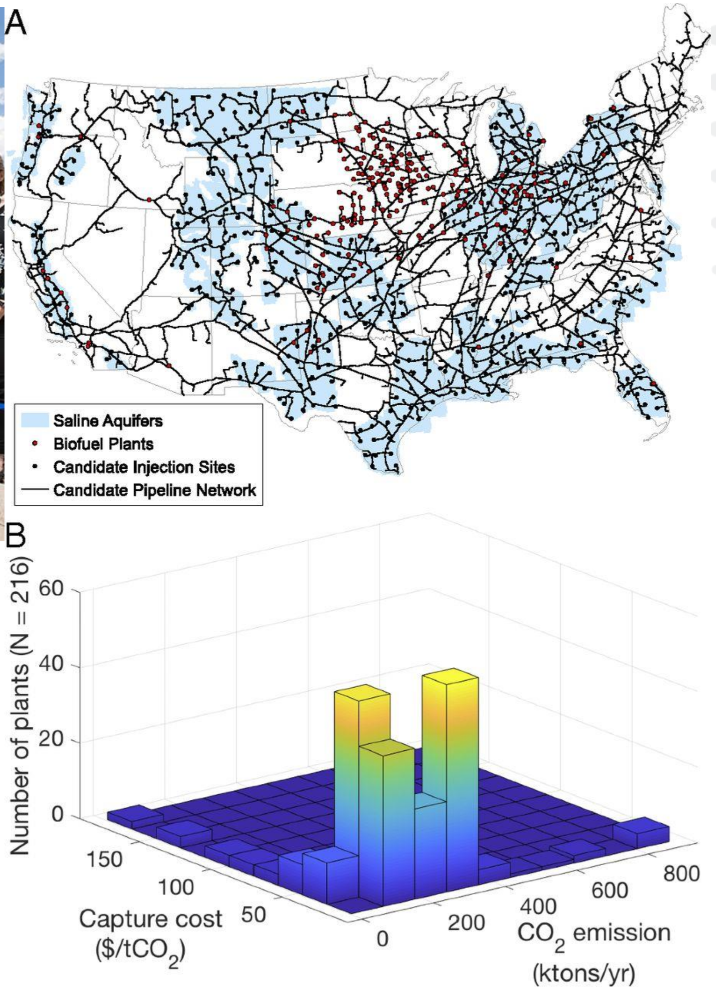


Unit processes to study

Optimizing for products would be most valuable

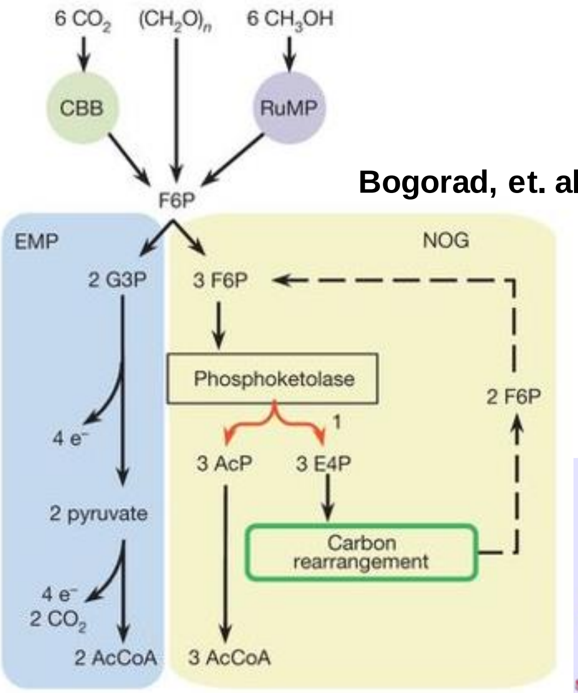
- Optimizing for grid stability is being demonstrated
- Optimizing for BECCS appears readily viable
- Optimizing for product synthesis is not currently possible – ARPA-E seeks to change what is possible



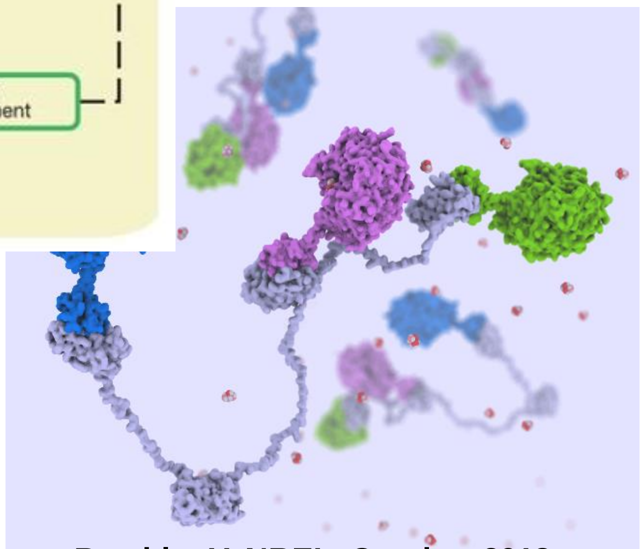
Sanchez et. al. PNAS, May 2018

Biochemical approaches to carbon optimized conversion

- Non-oxidative glycolysis
- De novo carbon rearrangement strategies
- Mixotrophic fermentation
- Cell-free biocatalytic conversion with renewable co-factor regeneration
- Other?

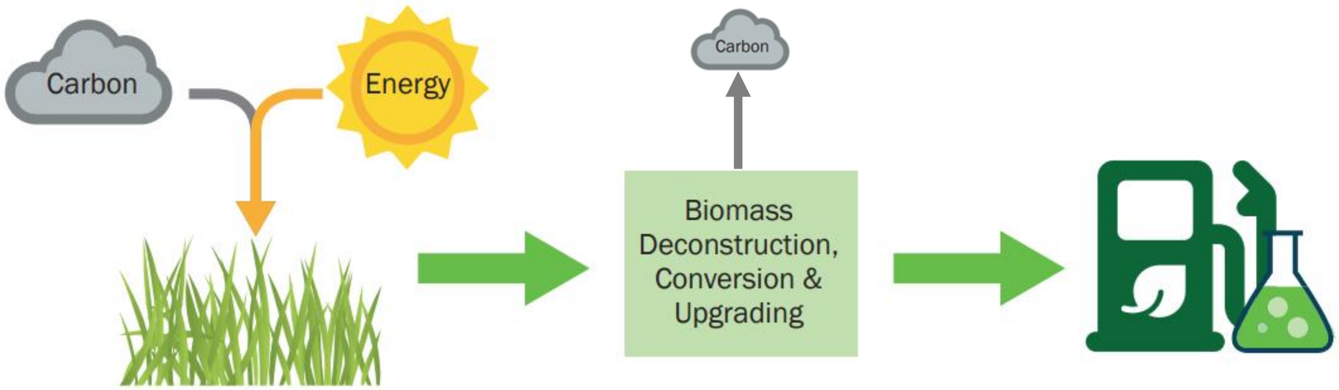


Bogorad, et. al. Nature, October 2013



Bomble, Y. NREL. October 2018

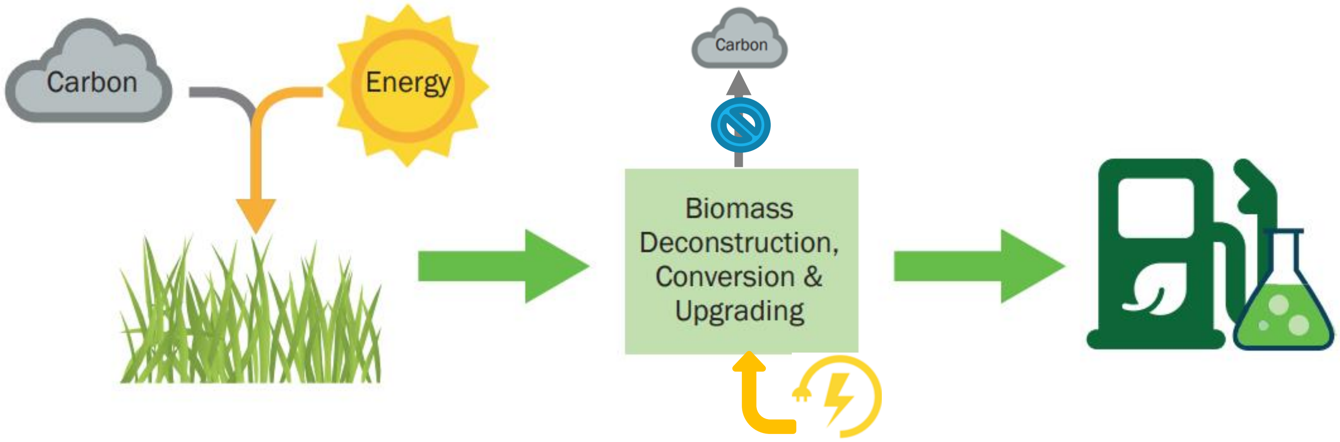
Traditional Fermentation



Sugar → Product + Carbon Dioxide

$$1.5C_6H_{12}O_6 \rightarrow 3C_2H_6O + 3CO_2$$

ECO-Fermentation



$$\text{Sugar} + \text{Reducing Equivalent} \rightarrow \text{Product}$$

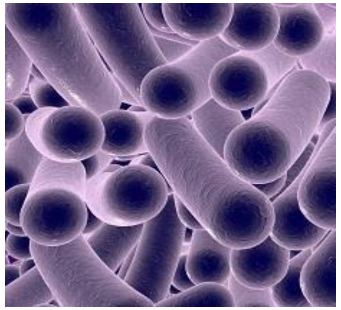
$$C_6H_{12}O_6 + 6H_2 \rightarrow 3C_2H_6O + 3H_2O$$

ECO-Fermentation

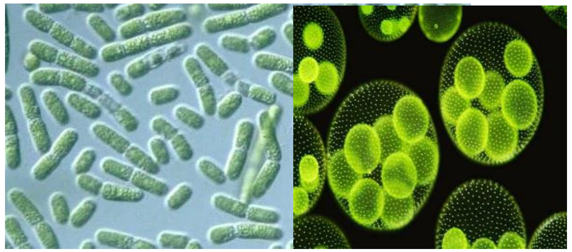
Common industrially relevant microbial platforms for fermentation

Yeasts (S.c, Y.l)

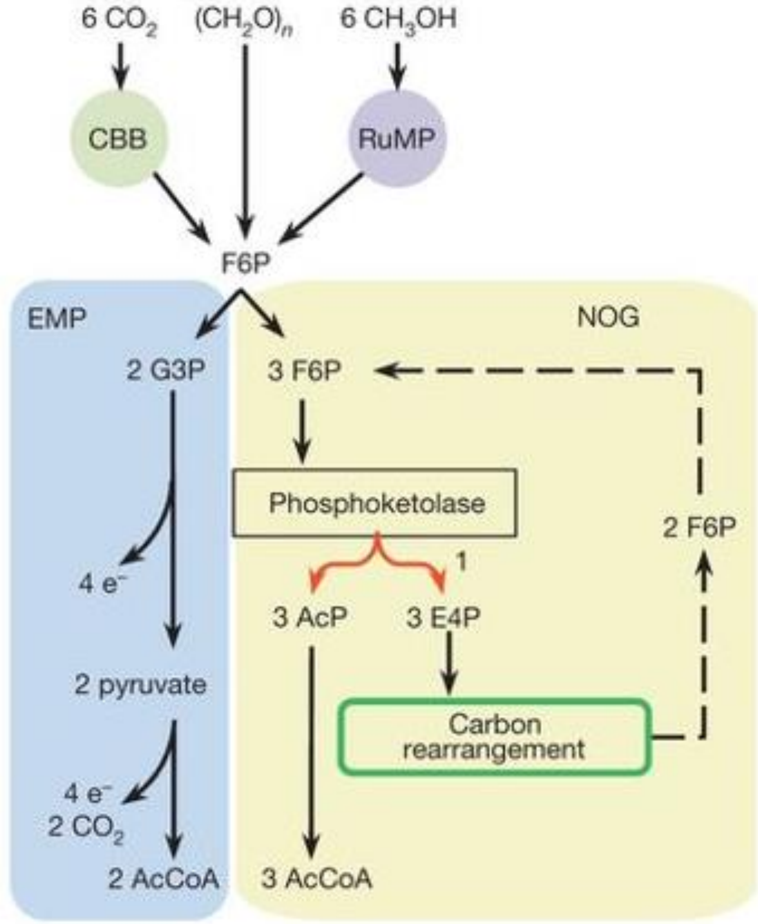
Acetogens (C. auto)



Cyanobacteria and Algae



Glycolysis and non-oxidative glycolysis routes to AcCoA

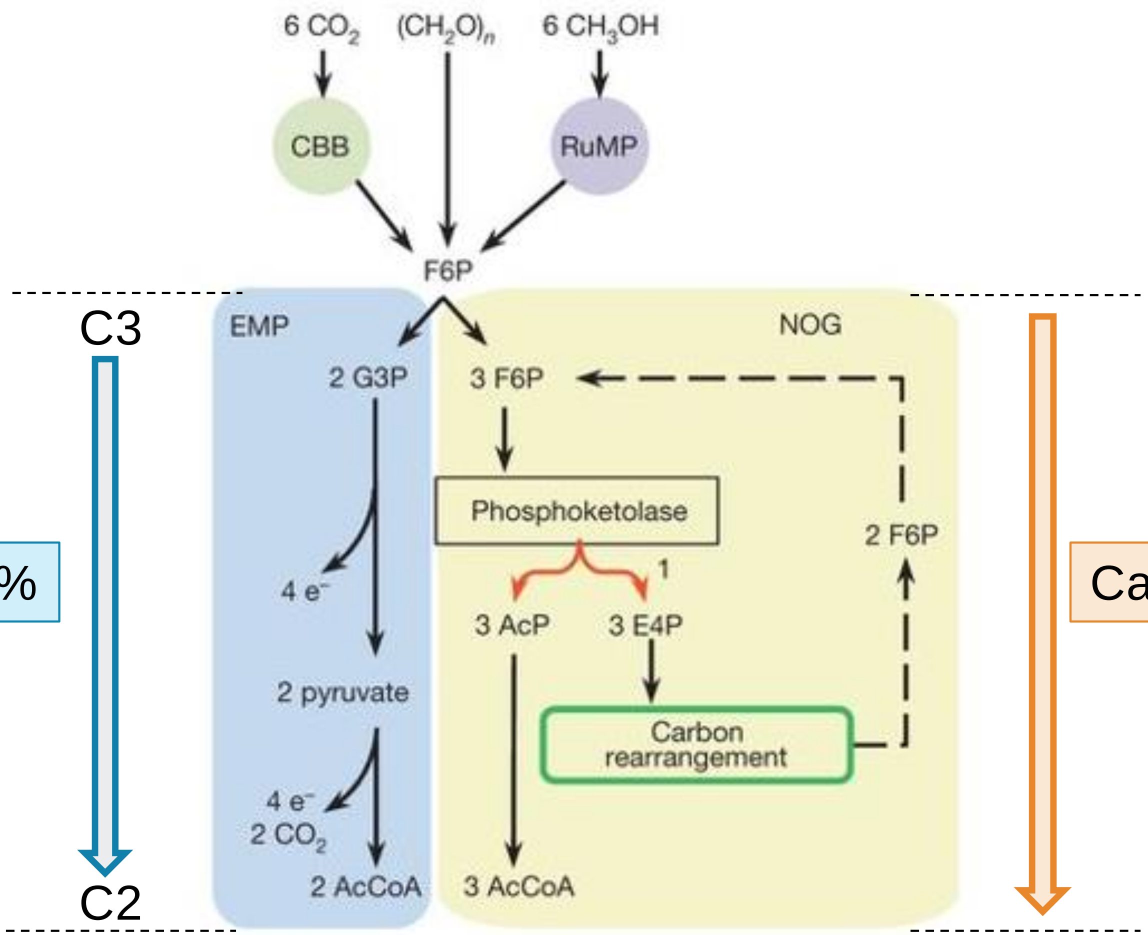


Bogorad, et. al. Nature, October 2013

ECO-Fermentation

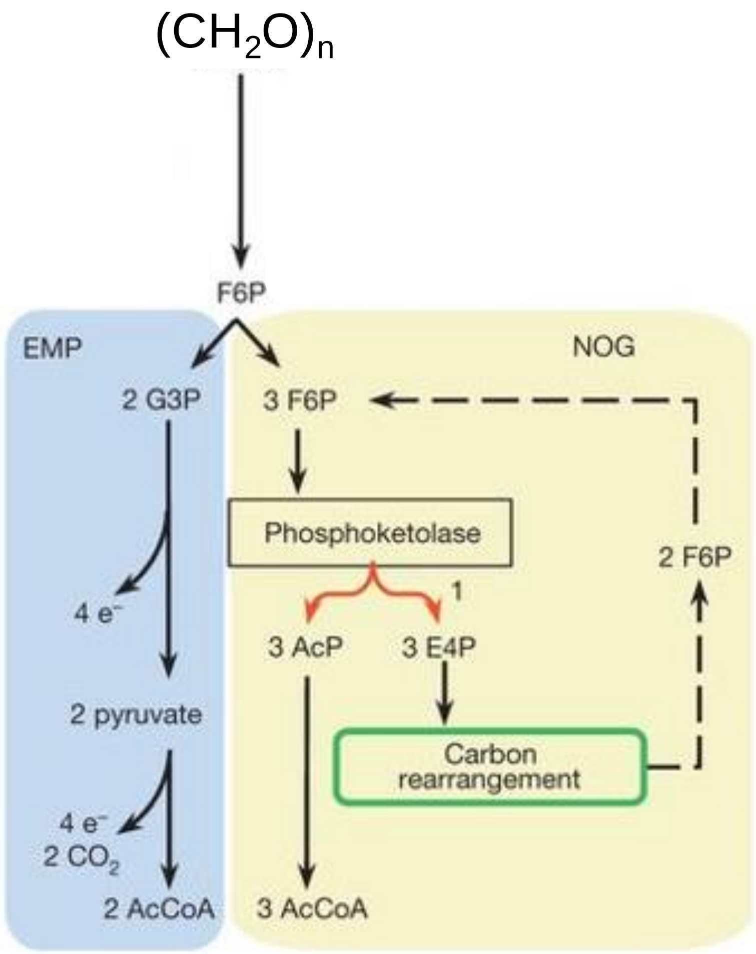
Traditional Glycolysis	Non-Oxidative Glycolysis (NOG)

Carbon Yield = 66%



Carbon Yield = 100%

ECO-Fermentation



Glycolysis (Oxidative)

$$1.5C_6H_{12}O_6 \rightarrow 3C_2H_6O + 3CO_2$$

Non-oxidative Glycolysis (NOG)

$$C_6H_{12}O_6 + 6H_2 \rightarrow 3C_2H_6O + 3H_2O$$

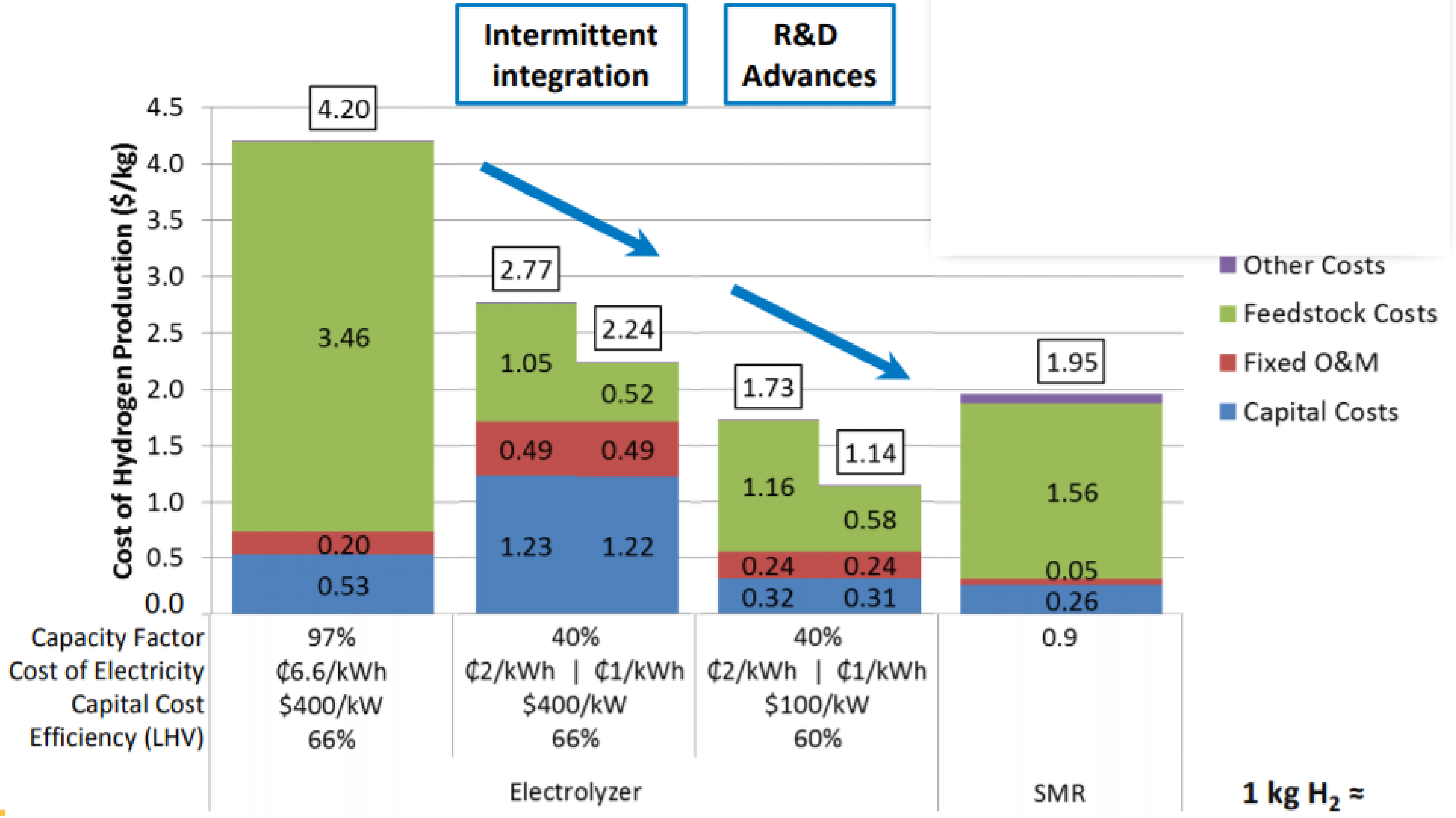
Based on stoichiometry when:
(0.65 kg-sugar)*($-sugar) < (0.087)*($-H_2)
It makes sense to do non-oxidative glycolysis

Sugar price = $0.35 - $0.4

Thus, when H_2 is less than $2.6 per kg it makes sense to consider NOG

Bogorad, et. al. Nature, October 2013

Prospects for low cost H_2 look good



1 kg H_2 ≈ 1 gallon of gasoline equivalent (gge)

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CHANGING WHAT'S POSSIBLE

Carbon Balance with SMR

Cost of H_2 via SMR is already less than $2 per kg

Non-oxidative (NOG)	$C_6H_{12}O_6 + 6H_2 \rightarrow 3C_2H_5OH + 3H_2O$
Methane steam reforming	$1.5\ CH_4 + 3H_2O \rightarrow 1.5\ CO_2 + 6H_2$
	$C_6H_{12}O_6 + 1.5\ CH_4 \rightarrow 3C_2H_5OH + 1.5\ CO_2$
Traditional Fermentation	$1.5C_6H_{12}O_6 \rightarrow 3C_2H_6O + 3\ CO_2$

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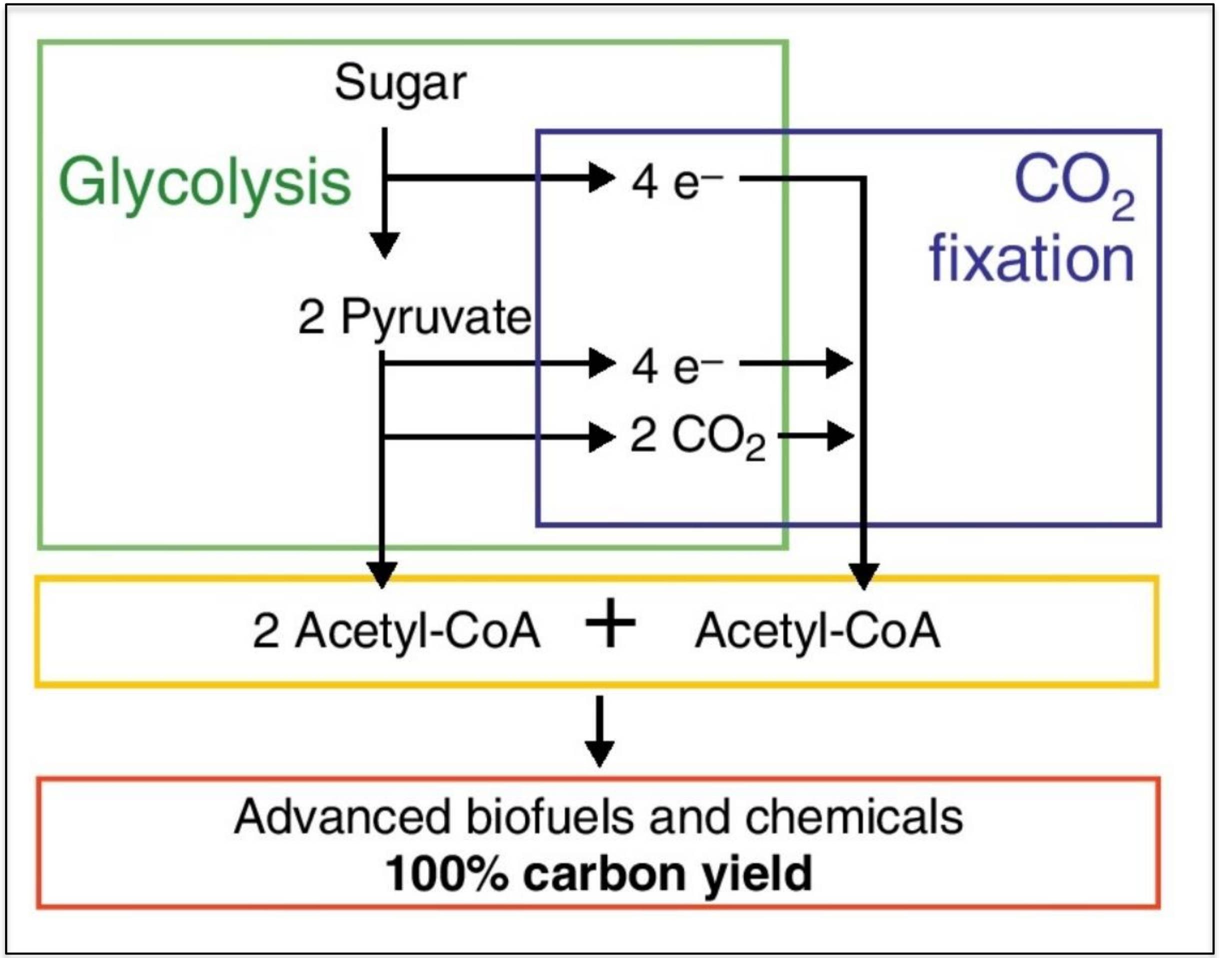
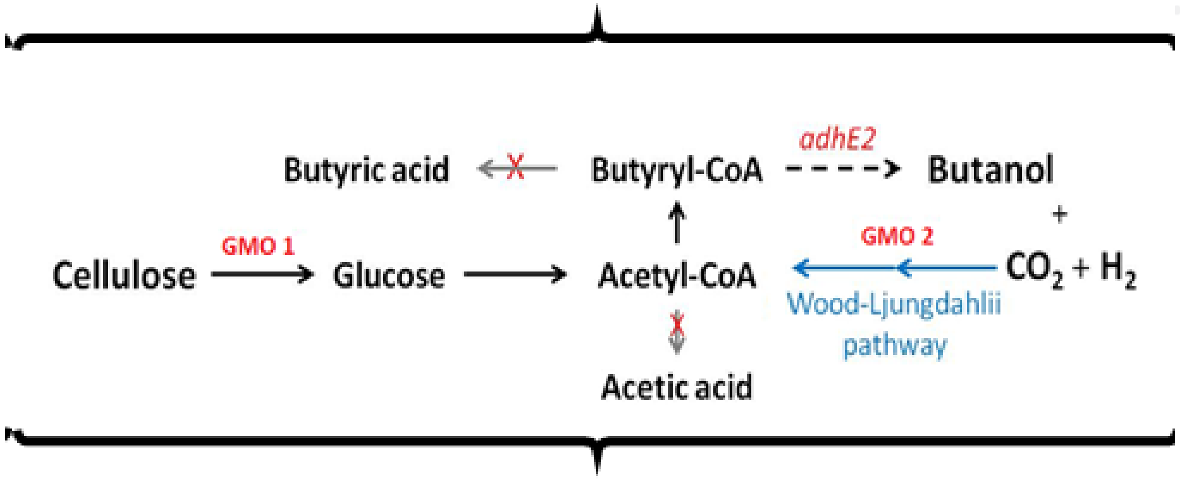
Mixotrophic and mixed culture fermentation

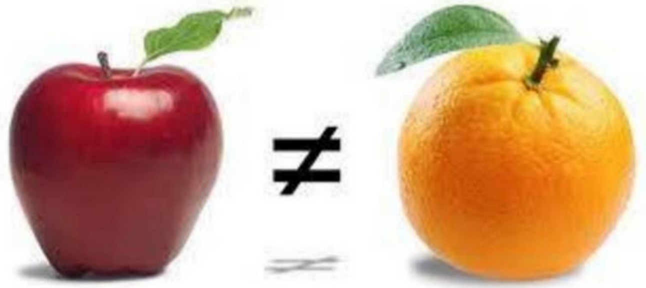




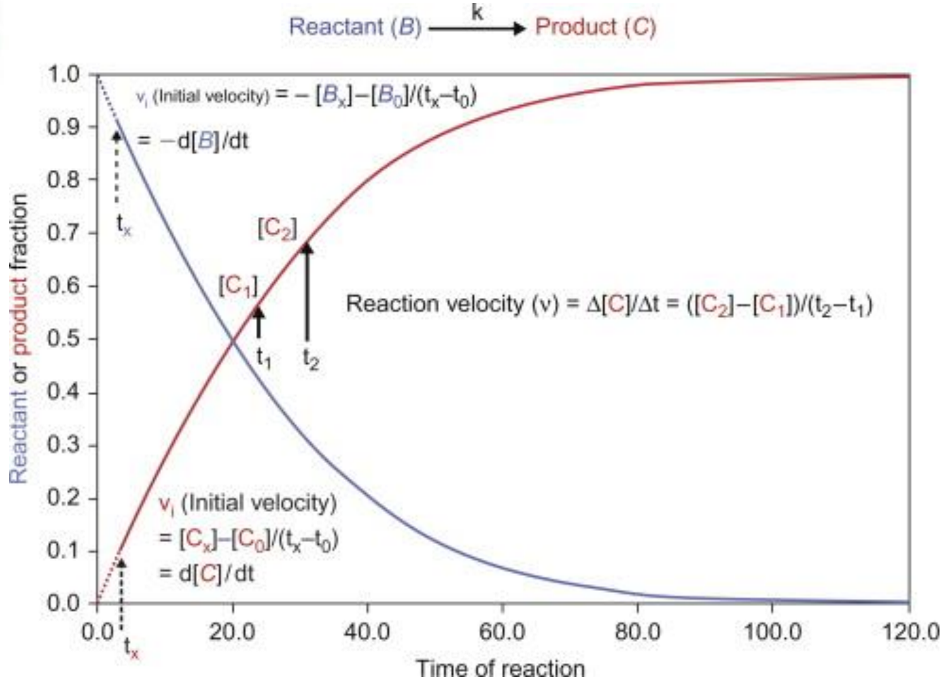
Fast et. al. Current Opinion in Biotechnology, June 2015

Reactor considerations for ECO-fermentation

New microbial platforms need to be matched with new and appropriately optimized fermentation systems

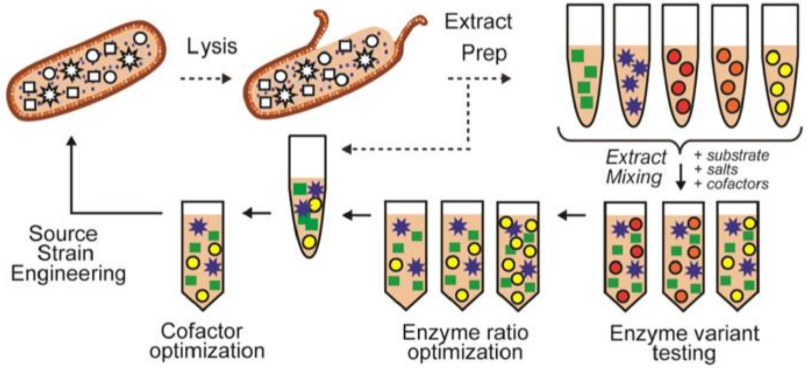


- Different reaction kinetics
- Reducing equivalent (H_2, formate, other) flux and toxicity
- Separations
  - New opportunities for low-C separations such as vacuum distillation

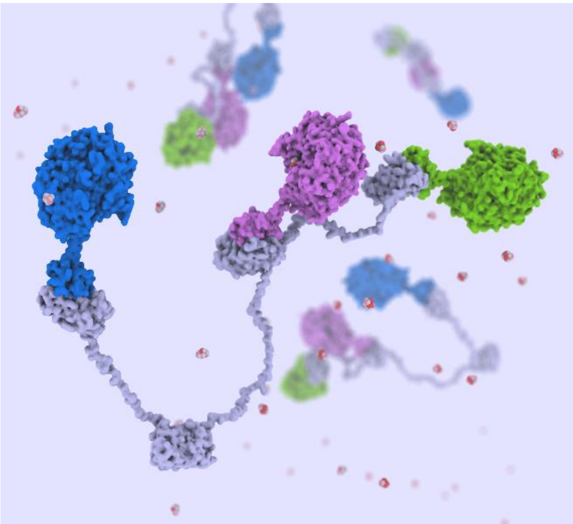


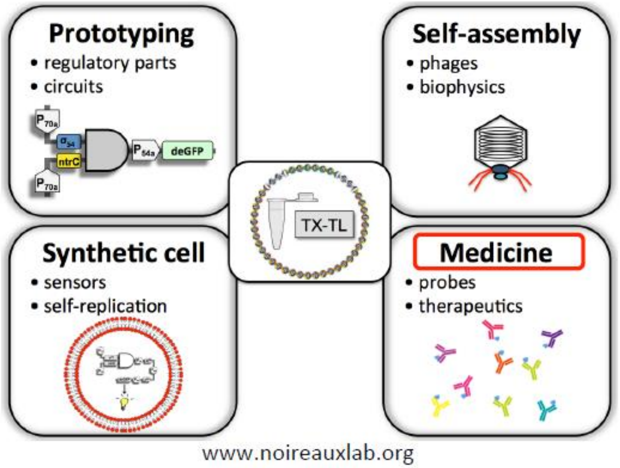
Cell-Free Synthetic Biology and Biocatalysis

Cell-free synthetic biology for prototyping

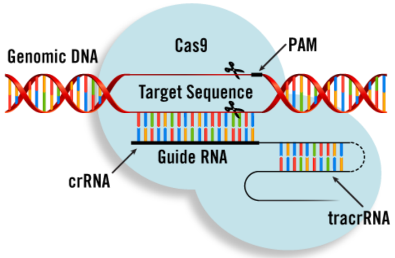


Cell-free biocatalysis



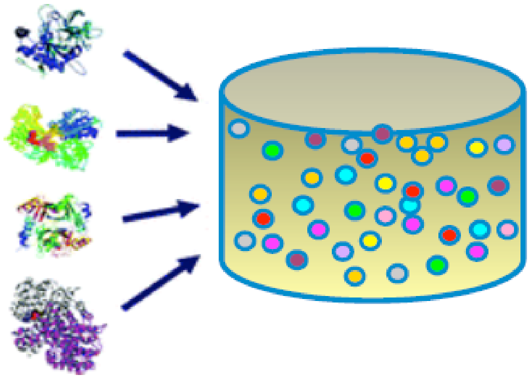


Implications for prototyping and future reactor design



- Cell-free bioconversion
  - Fast reaction rates
  - Broad reaction conditions
  - Reactor design for desired reaction kinetics
  - Complete othoganality
  - Novel products

- Challenges
  - Unstable enzymes
  - Enzyme production
  - Expensive co-factors
  - Co-factor engineering/ regeneration



Zhang. (2011) ACS Catalysis 1: 998

What if carbon loss could be avoided during biomass conversion (/CO_2 utilization)?

Fuel and products

50% more

ethanol from the same sugar input

GHG Emissions Reductions

Additional (Carbon) Value

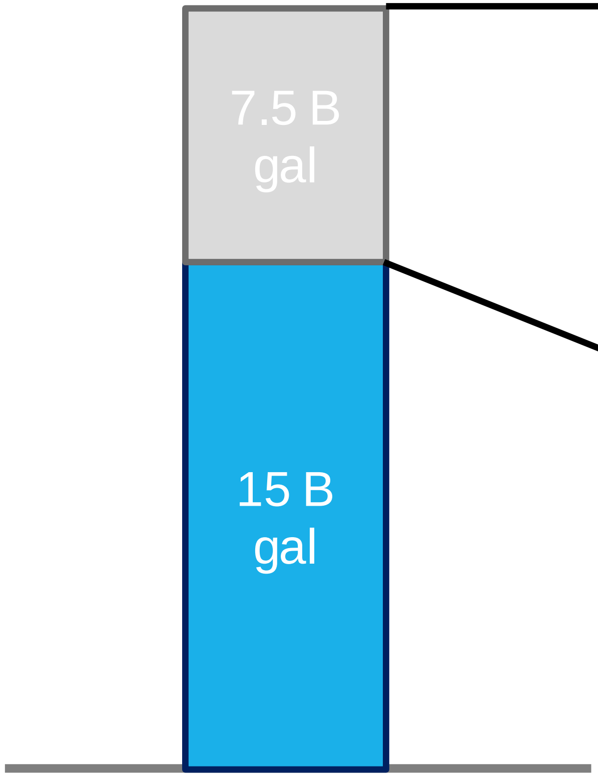
CALIFORNIA AIR RESOURCES BOARD

CALIFORNIA AIR RESOURCES BOARD | CARB

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Implications for ECO-Fermentation

**50% more
ethanol from the same sugar input**



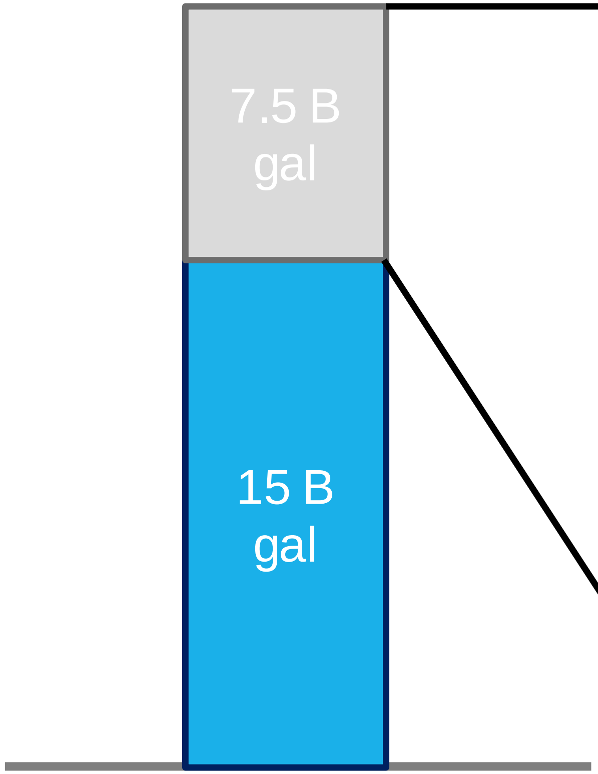
Currently (2019)

- Land savings
- 13.4 million acres

West Virginia = 15.5 M acres

Implications for ECO-Fermentation

**50% more
ethanol from the same sugar input**

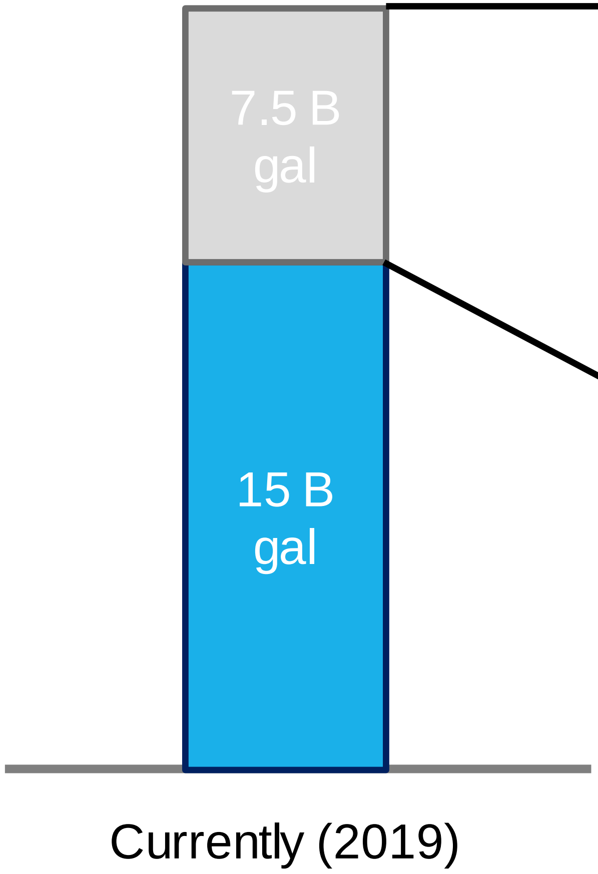


Currently (2019)

- Emissions
  - 15 – 22 g/MJ of ethanol
  - 18 – 27 Billion kg of CO_2
  - Equivalent to the electricity emissions from 3,200,000 U.S. homes

Implications for ECO-Fermentation

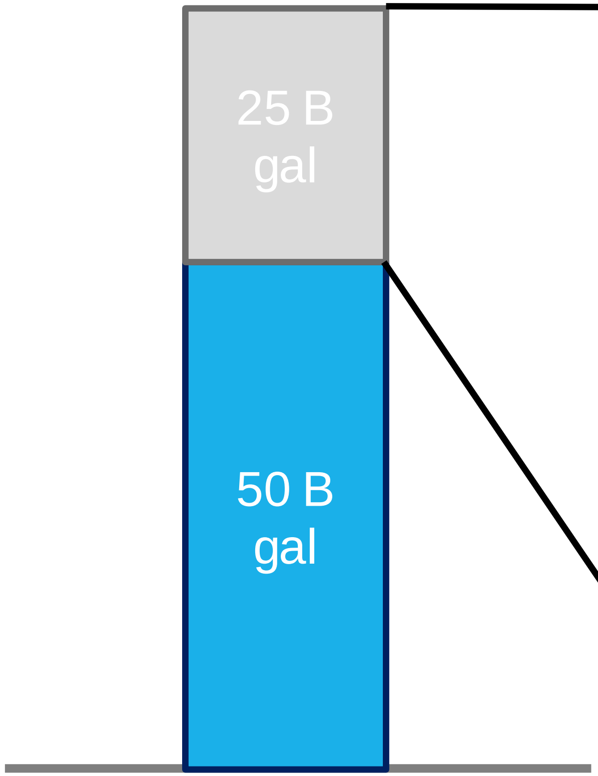
**50% more
ethanol from the same sugar input**



- Environmental Attributes
  - Fuel credits (extra)
    - LCFS - $8.5 Billion per year
    - RFS - $5.7 – 19 Billion per year
  - CO_2 Utilization (new)
    - $35/ton
    - $5.5 Billion per year

Implications for ECO-Fermentation

50% more
product from the same biomass input



Billion Ton Bioeconomy

- Land saved
  - 45 M acres equivalent to the size of Missouri

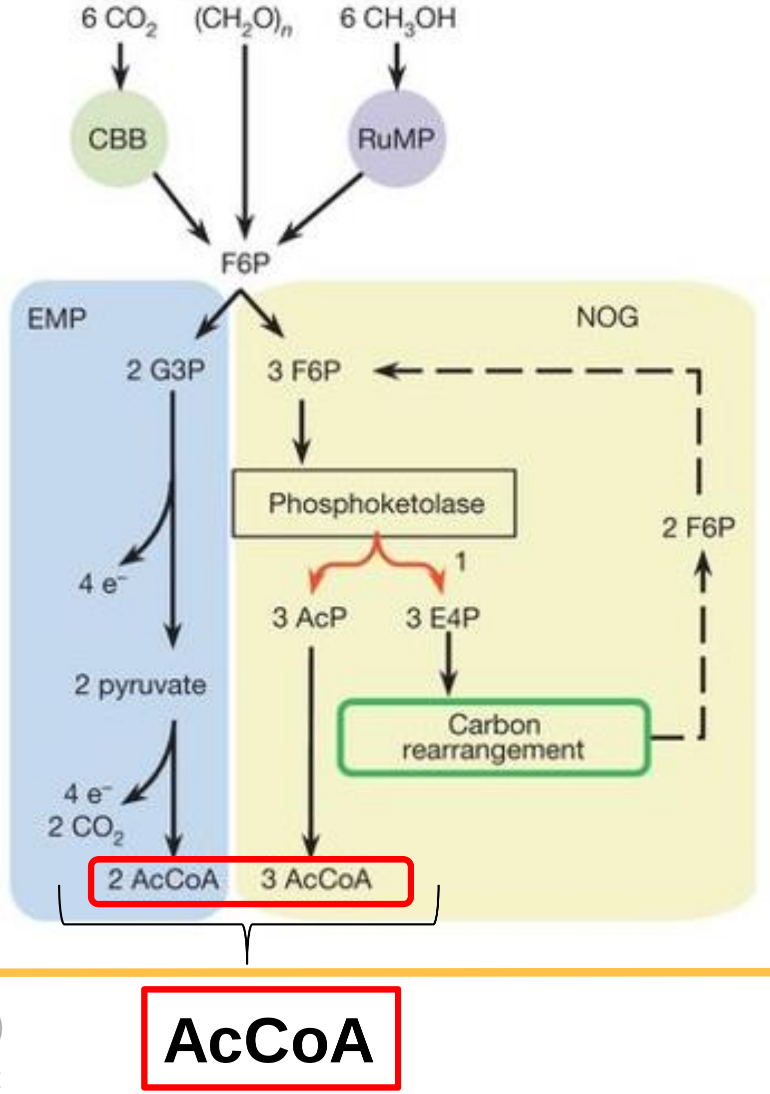
- Emissions
  - 60 – 90 Billion kg CO_2
  - 10,600,0000 U.S. homes

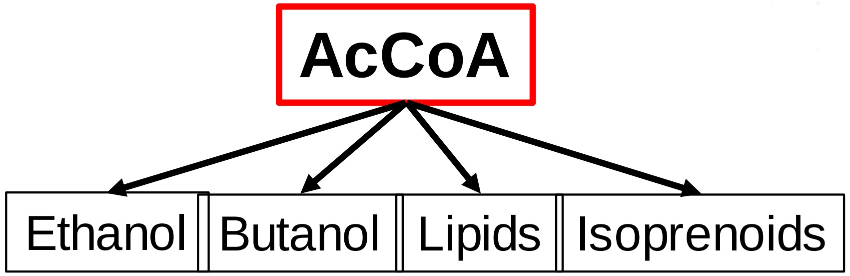
- Value
  - Fuel credits (extra)
    - LCFS – $28 Billion per year ($189/MT)
    - RFS – $19 – $63 Billion per year
  - CO2U (new)
    - $35/ton
    - $18 Billion/year

These estimates do not include implications for 50 billion pounds of biobased chemicals and products

Beyond ethanol: downstream synthesis opportunities

Regardless of the downstream product the re-designed metabolism has substantial implications for carbon management and energy





jbei Joint BioEnergy Institute

Agile BioFoundry

DARPA

Leveraging synthetic biology to improve metabolic carbon flux will avoid energy requirements and unnecessary carbon and land waste

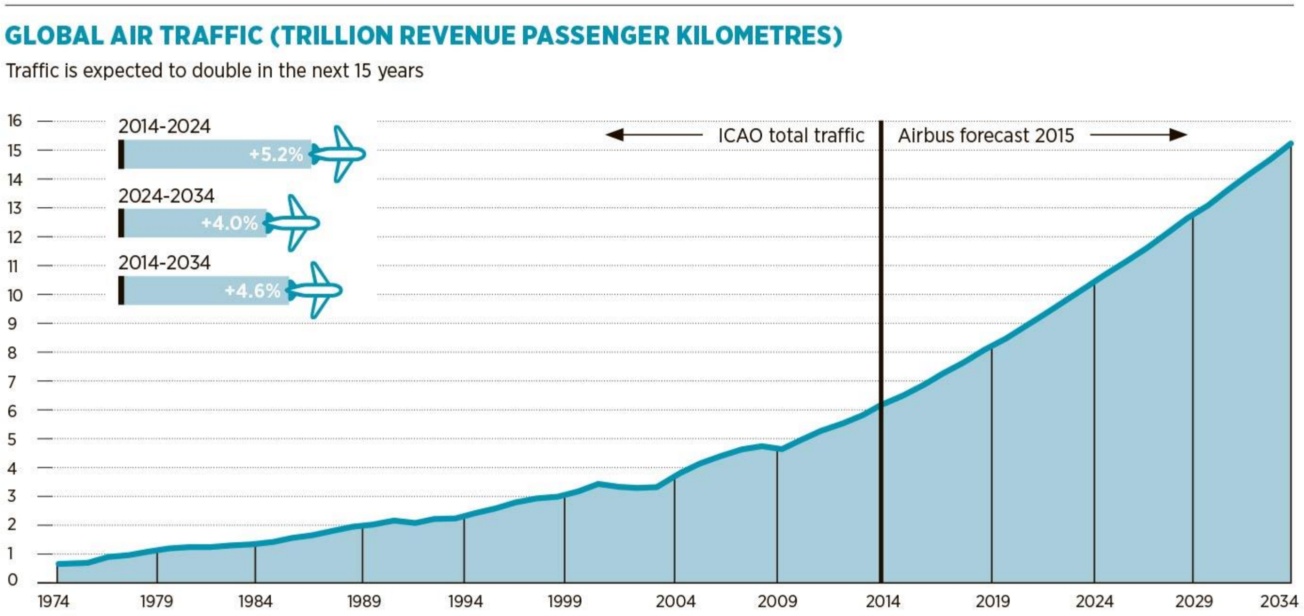
Ethanol as a platform intermediate

Ethanol can serve as a platform for downstream fuel and chemical synthesis
e.g. Ethanol-to-jet

LanzaTech
capturing carbon. fueling growth.

Pacific Northwest
NATIONAL LABORATORY

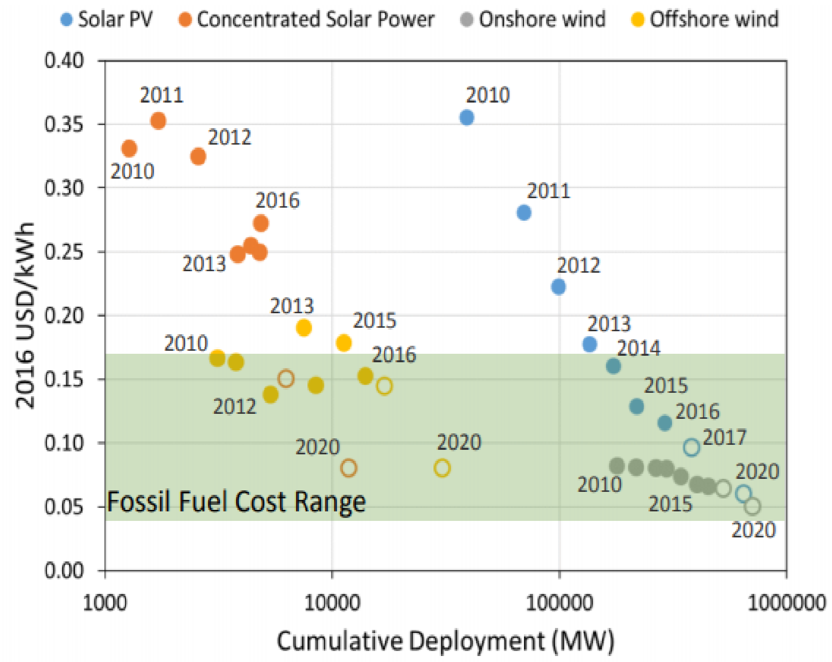
Ethanol → Dehydration → Oligomerization → Hydrogenation → Fractionation → Jet / Diesel / Gasoline



Source: International Civil Aviation Organization (ICAO)/Airbus 2015

Summary

New Drivers for Innovation in the Bioeconomy

Carbon / GHG Emissions	Land	Low-cost, low carbon e⁻
		

- Future incentive structures will promote land use and carbon reductions
- Develop technologies that leverage low-cost, low carbon e-, to profit from such incentives

Workshop to engage stakeholders and elicit expert input

Technology whitespace to be considered	Expertise to engagee

- Biotechnologies for carbon optimized bioconversion, specifically:
  - Non-oxidative glycolysis
  - Mixotrophic fermentation
  - Cell-free biocatalysis and stand alone cell-free conversion platforms

All strategies to be able to accommodate reducing equivalents to optimize for carbon efficiency

- Academic expertise
  - Conversion – thermochem, biochem, synbio, electrochem
  - Systems integration
  - TEA/LCA
- Industry and NGOs
  - Oil/gas
  - Biorefiners
  - Ag/Enviro/Climate NGOs
- Other government agencies/offices
  - DOE: EERE - BETO, FCTO, FE
  - EPA: OTAQ
  - USDA: OCS
  - CARB

Workshop to identify key items for a potential new program FOA

- Opportunities
  - Energy products
  - Economic efficiency
  - Carbon management

- Challenges
  - Lack of established community
  - Technical
    - Bioengineering

- Needs
  - Research
  - Community
  - Vision

How do we realize 100% carbon efficient bioconversion?

Develop bioconversion pathways and strategies capable of accommodating external reducing equivalents to optimize for carbon efficiency.

Biofuels, Bioproducts, Biochmeicals, and Materials