Emerging Technologies to Support the SAF Grand Challenge 2050 Goal

Routes to achieving Net-Zero Fuels and e-fuels

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Goals

- Overview and context
- Analysis for low carbon intensity fuels and efuels
- CO_2 Reduction and Upgrading for E-fuels (CO_2RUE) Consortium

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Sustainable Aviation Fuel Grand Challenge MOU: 9-8-2021

In recognition of these myriad benefits, DOE, DOT, and USDA are launching a government-wide Sustainable Aviation Fuel Grand Challenge (the Grand Challenge) to reduce the cost, enhance the sustainability, and expand the production and use of Sustainable Aviation Fuel (SAF) that achieves a minimum of a 50% reduction in lifecycle greenhouse gas (GHG) compared to conventional fuel to meet a goal of supplying sufficient SAF to meet 100% of aviation fuel demand by 2050.

Through this MOU, the Parties intend to accelerate the research, development, demonstration, and deployment (RDD&D) needed for innovative solutions and technologies and the policy framework to enable an ambitious government wide commitment to scale up the production of SAF to 35 billion gallons per year by 2050. A near-term goal of 3 billion gallons per year is established as a milestone for 2030.

1) The need to develop strategies that significantly reduce the carbon intensity of aviation fuels

2) The need to get enough renewable carbon to meet those demands

Reducing the carbon intensity of SAF pathways

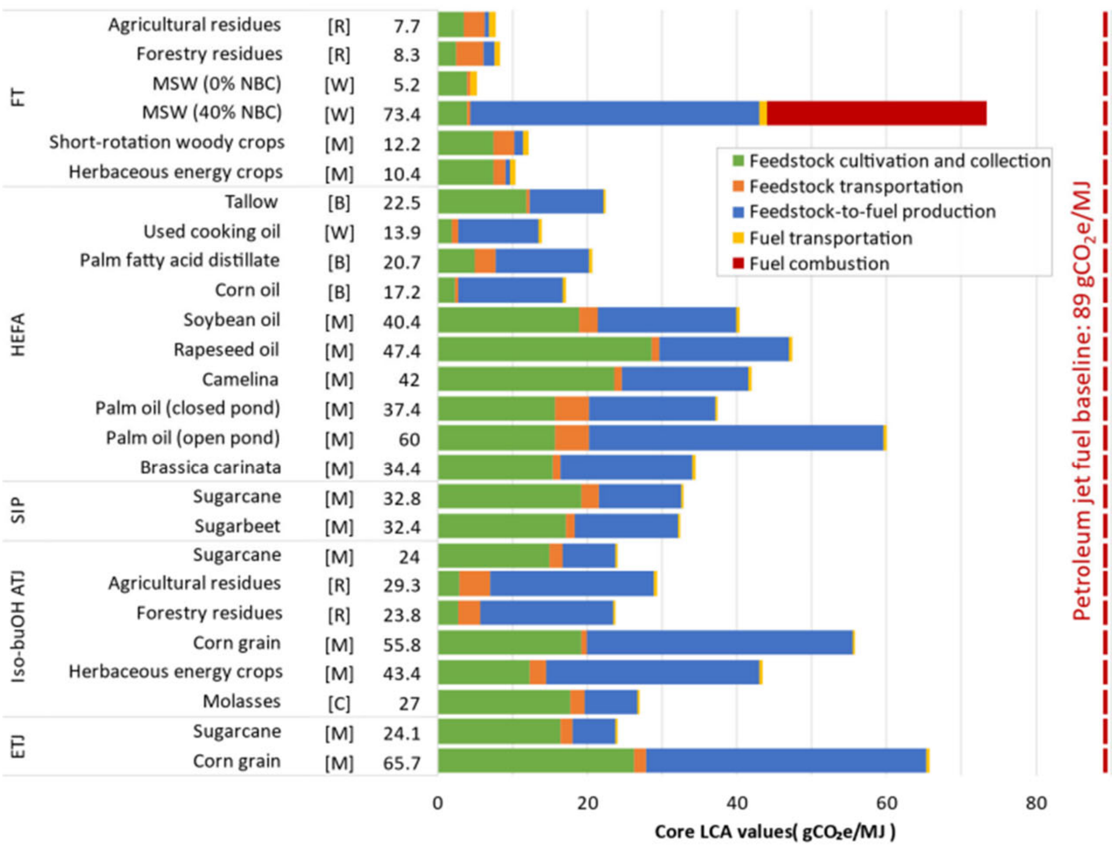


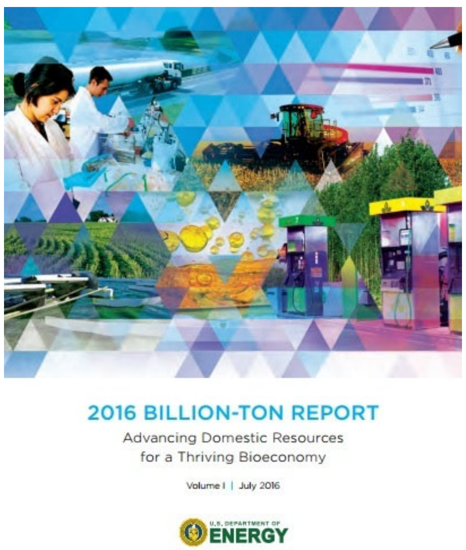
Figure 2. Default core LCA values of SAF production pathways approved by ICAO to date. (NBC: non-biogenic carbon content)

Prussi, et al. *CORSIA: The First Internationally Adopted Approach to Calculate Life-cycle GHG Emissions for Aviation Fuels*

While some of the approved SAF pathways hit the 50% threshold on paper, its clear that:

- The large volume feedstocks and pathways in the US are still above that threshold and need further progress
- Deep decarbonization (beyond 50%) will require more work

Acquiring enough renewable carbon to meet the demand



The US has the potential to produce at least 1B tons of biomass (agricultural, forestry, waste, and algal materials) on an annual basis without adversely affecting the environment

- 36B gallons of SAF = 600M tons of biomass
- ~9B gallons of marine fuel (EIA 2019) = 150M tons of biomass
- ~5B gal of diesel (~10% of today's use) = 80M tons of biomass
- 100M tons of chemicals (~50% of today's market) = 400M tons of biomass
- ~ 500M tons of carbon removal via BECCS or BiCRS = 500M tons of biomass (assumes ~half of CDR uses biomass)
- **TOTAL = 1.8B tons of biomass**

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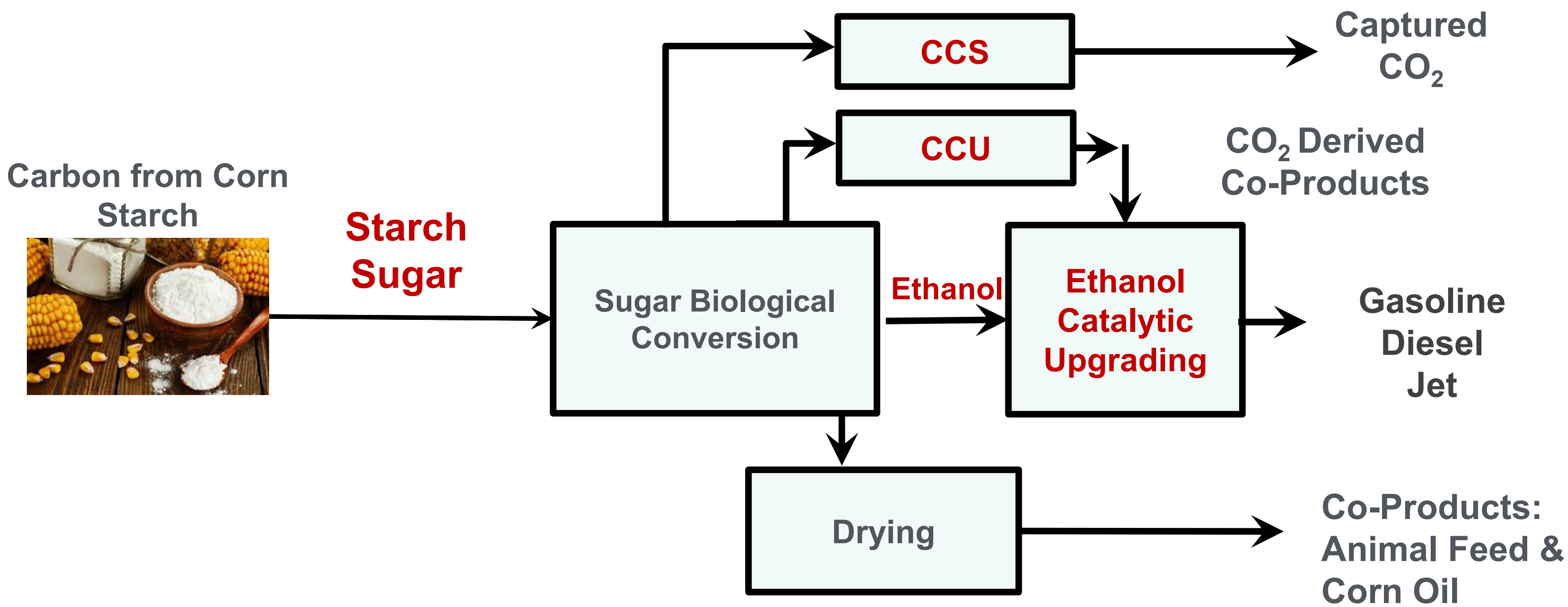
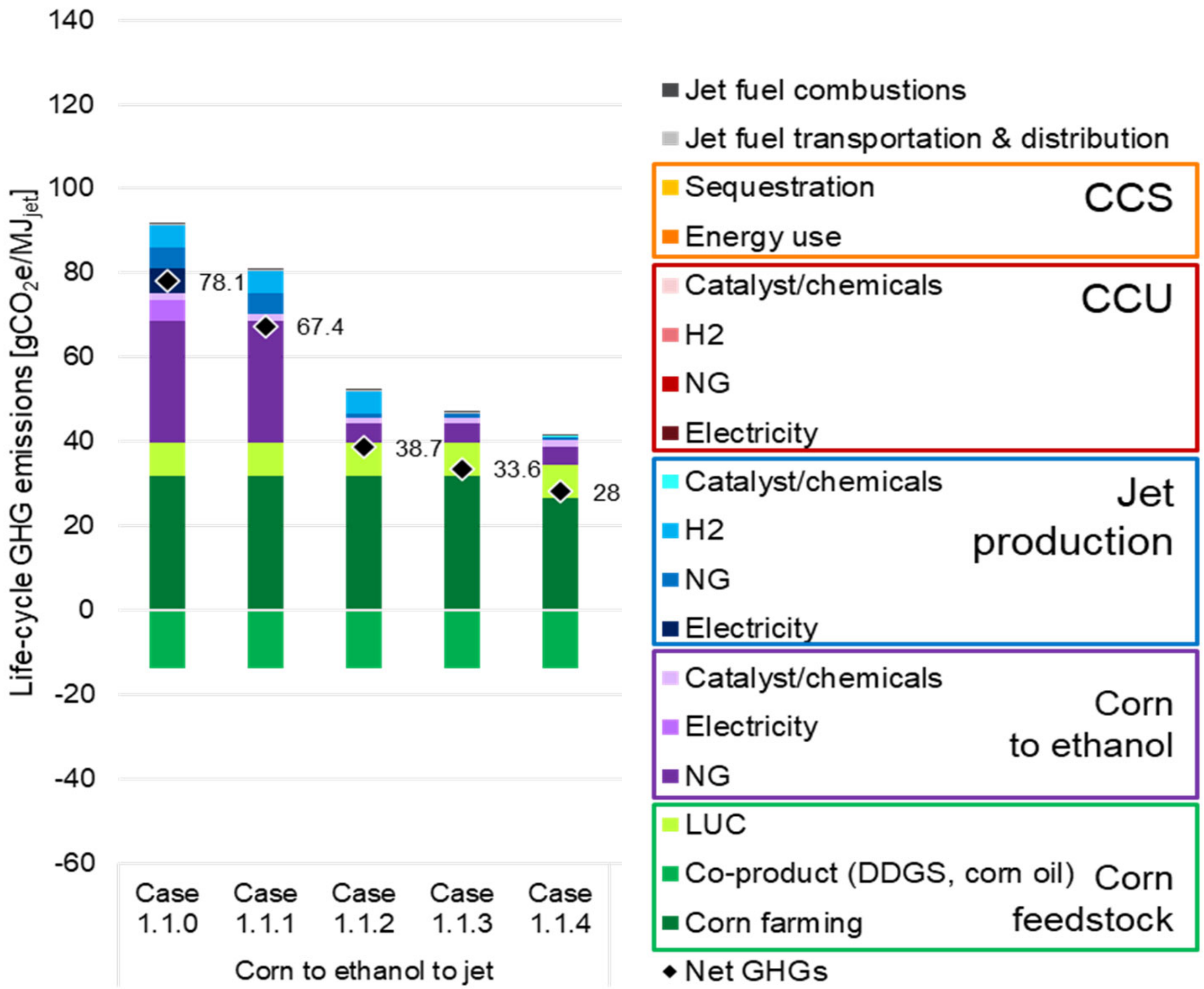
Enabling low CI Fuels in 2050 example: Corn ETJ



Corn ETJ (with mitigation) Lifecycle assessment



1.1.0: Base (no mitigation)

- H_2 cost (NG SMR): $1.38 kg H_2
- H_2 base CI: 79 gCO_2/MJ
- Electricity: 6.8¢/kWh , 440 gCO_2/kWh
- NG: 69 gCO_2/MJ

1.1.1: **Renewable elec.** (per kWh)

- 2¢/6.8¢/10¢
- 0g CO_2/kWh

1.1.2: Using **RNG** for on-site heat

- Landfill gas ($7/$13/$19 per MMBTU)
- 11 gCO_2/MJ

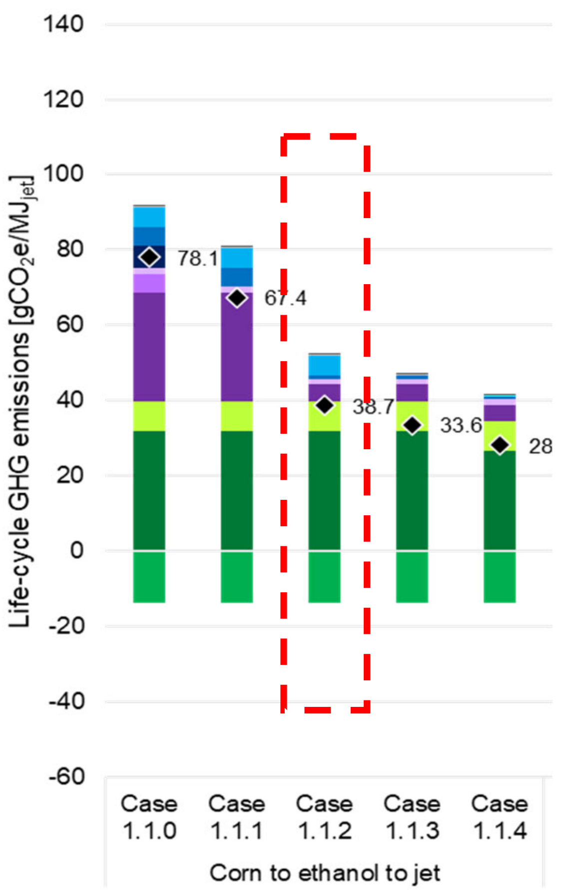
1.1.3: **Renewable PEM H_2** (0g CO_2/kg)

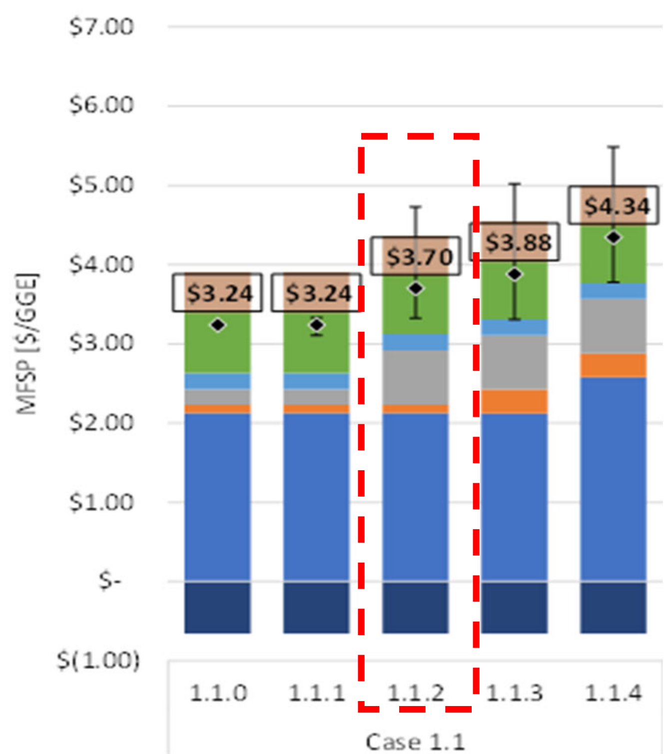
- H2 Cost assumptions (per kg): $1.38/$4.50/$6.35

1.1.4: **Renewable NH_3** on-field

- Made from renewable H_2

TEA and LCA of Corn ETJ





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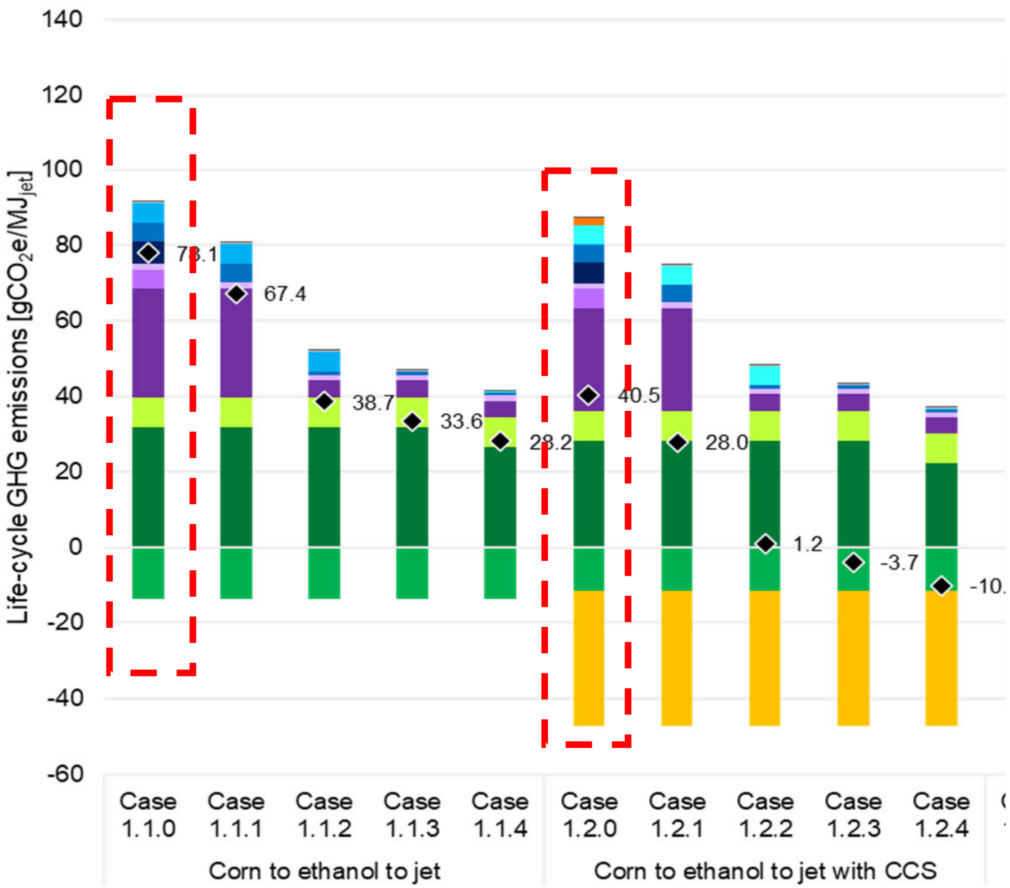
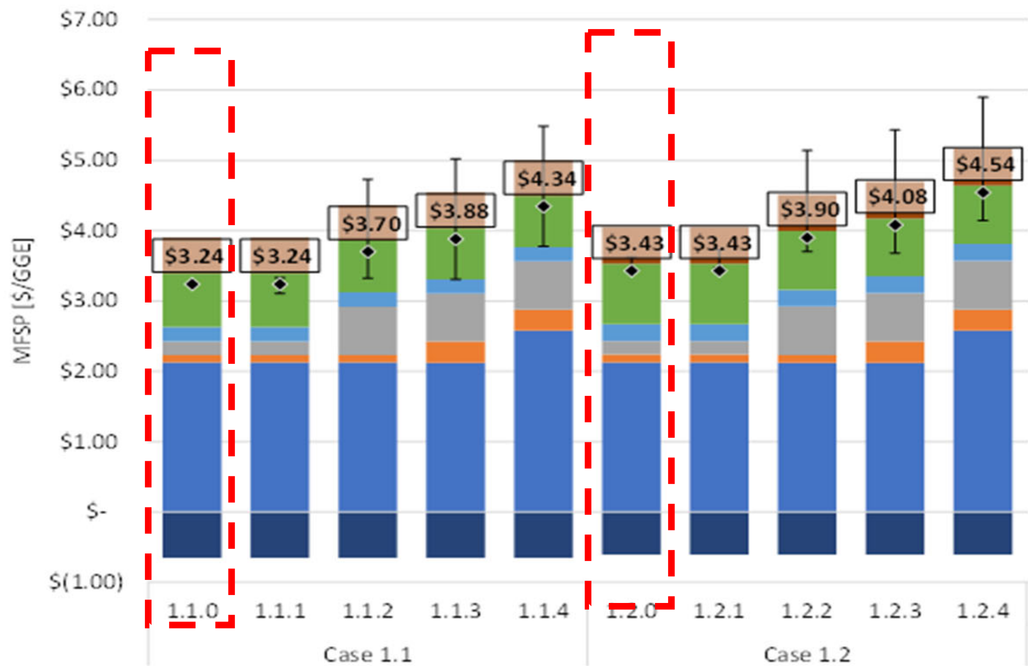
TEA and LCA of Corn ETJ + CCS





<u>Takeaway</u>: CCS cuts CI nearly in half and is lower cost (19¢/gal) than other mitigation strategies

0 = Base 1 = RE 2 = RNG 3 = Clean H2 4 = Green NH3

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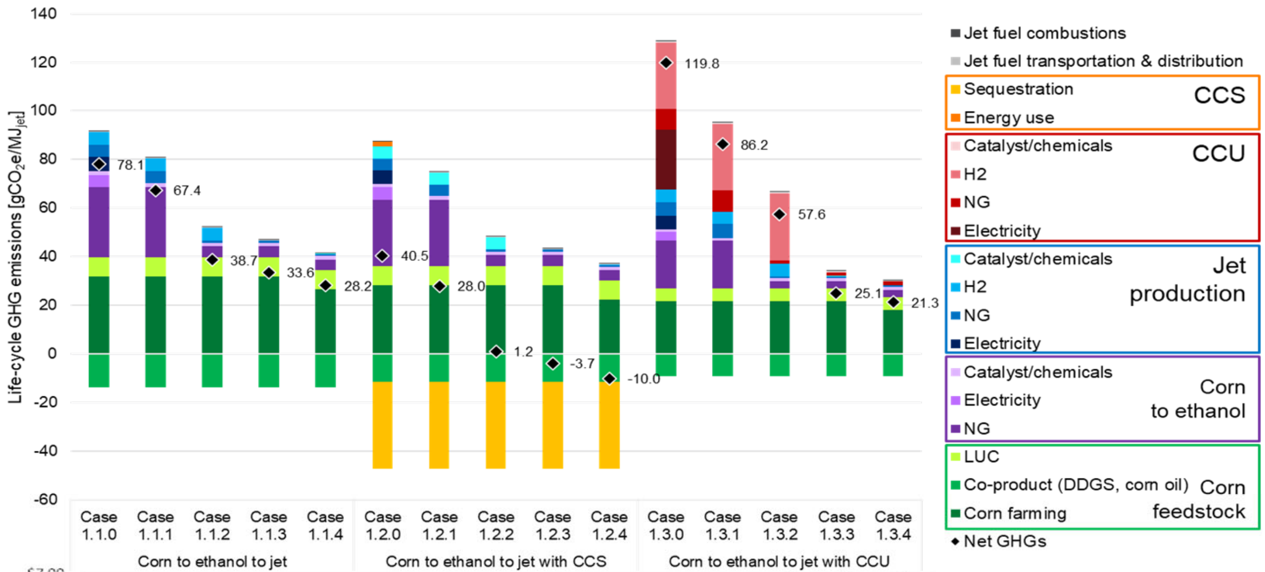
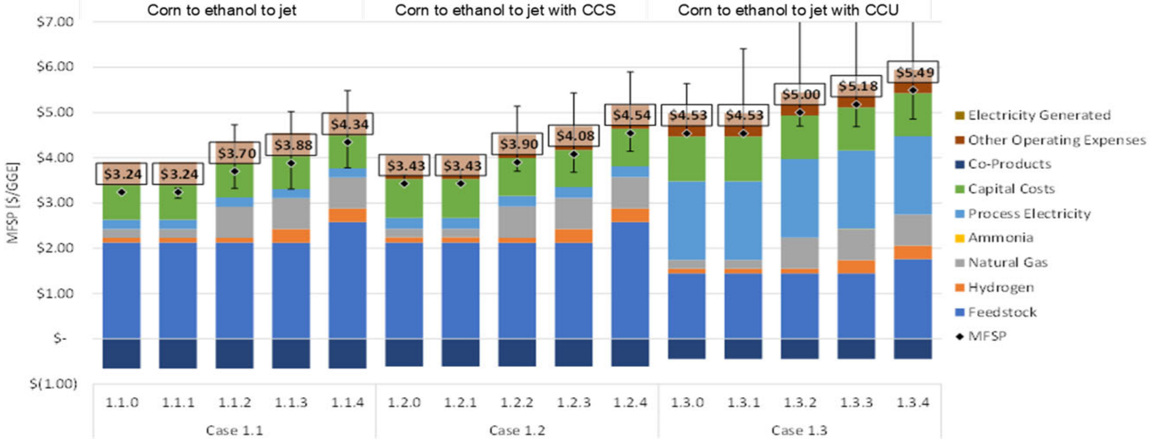
TEA and LCA of Corn ETJ + CCS or CCU





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CCU provides a route to increased volume of SAF (~50%) but is more expensive even with aggressive electricity price estimates AND requires significant amounts of renewable electricity and H2 to achieve attractive carbon intensities.

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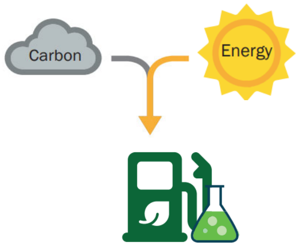
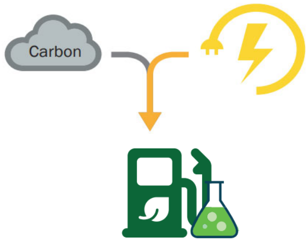
E-fuels

- Interchangeably called *synthetic fuels*, *power-to-liquids*, *power-to-gas* or *electrofuels*
- At its core, e-fuels are made by converting electricity into chemical bonds
- E-fuels provide an option for tapping into a vast renewable carbon resource
- E-fuels can have a very low carbon intensity IF they are made with renewable electricity



"Conventional biofuel"



"E-fuel"

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Near term e-fuel pilot project

MARQUIS

LanzaTech

Project Title: Carbon Refining: Corn Ethanol 2.0

Principal Investigator: Jennifer Aurandt-Pilgrim

Key Partners: LanzaTech

Proposed Total Project Cost: $8.5M DOE funds

- Marquis will host, commission, and operate a LanzaTech skid-mounted gas fermentation pilot plant at their Hennepin, IL biorefinery
- CO_2 from fermentation off-gas will be combined with and low CI H_2 and fed to the gas fermentation reactor
- Targets ethanol at 70% GHG reduction

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Broad technology space of CO2 reduction

H_2-mediated Conversion Technologies

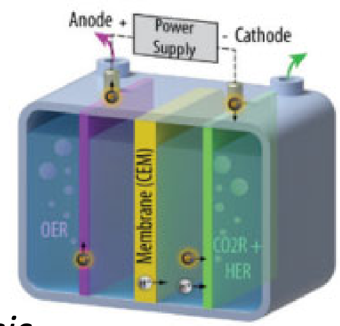
$CO_2 + H_2 \rightarrow CO + H_2O$
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Fischer-Tropsch
Reverse Water-gas Shift
Catalytic Hydrogenation to Methanol
Methanol to Olefins
Methanol to Gasoline

↑Heat, ↑Pressure, ↑Scale, ↑TRL

Electron-mediated Emerging Technologies

$CO_2 + 2e^- + 2H^+ \rightarrow CO + H_2O$
$2CO_2 + 12e^- + 12H^+ \rightarrow C_2H_4 + 4H_2O$



Electrolysis

Non-thermal Plasma

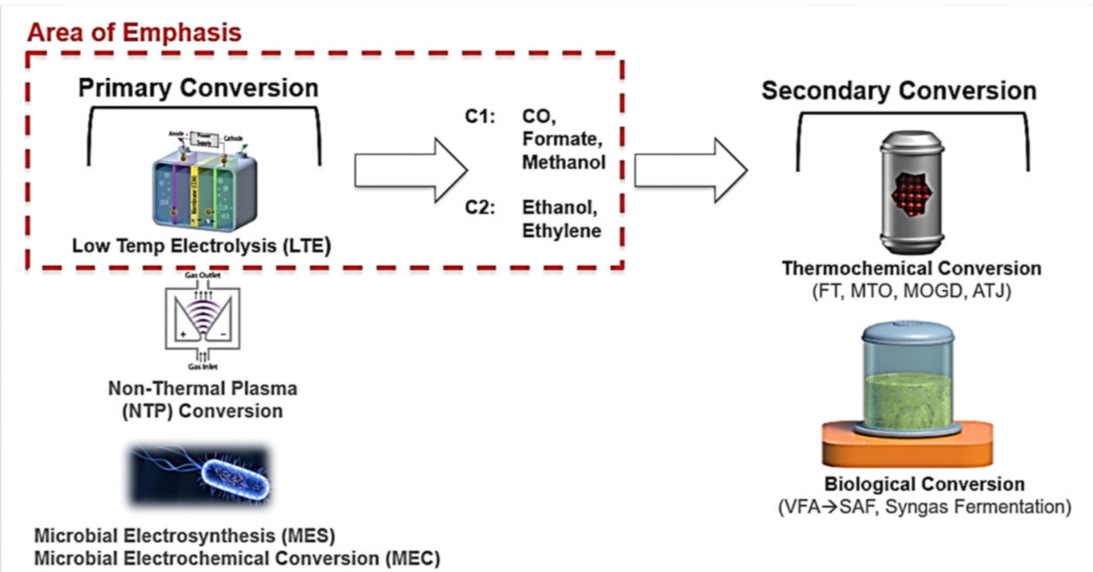
Microbial Electrosynthesis

↓Heat, ↓Pressure, ↓Scale, ↓TRL

Assessing the technology gaps that are good R&D targets

How to drive decarbonization of fuels and chemicals by 2050?

- *Where is the "white space"?*
- *Where are the opportunities for applied R&D across **low-to-moderate TRL**?*
- *What are the economic and environmental targets that should be achieved?*



Commercializing CO_2-based Fuels and Chemicals by 2050: R&D Gaps and Opportunities in the Direct Electrification of CO_2 Conversion

R. Gary Grim, Jack Ferrell, Zhe Huang, Ling Tao, Mike Resch

National Renewable Energy Laboratory

- *Availability of CO_2*
- *Identification of promising chemicals*
- *Strategic R&D needs*
- *Accelerated testing needs*
- *Commercialization timelines*
- *Technical targets*

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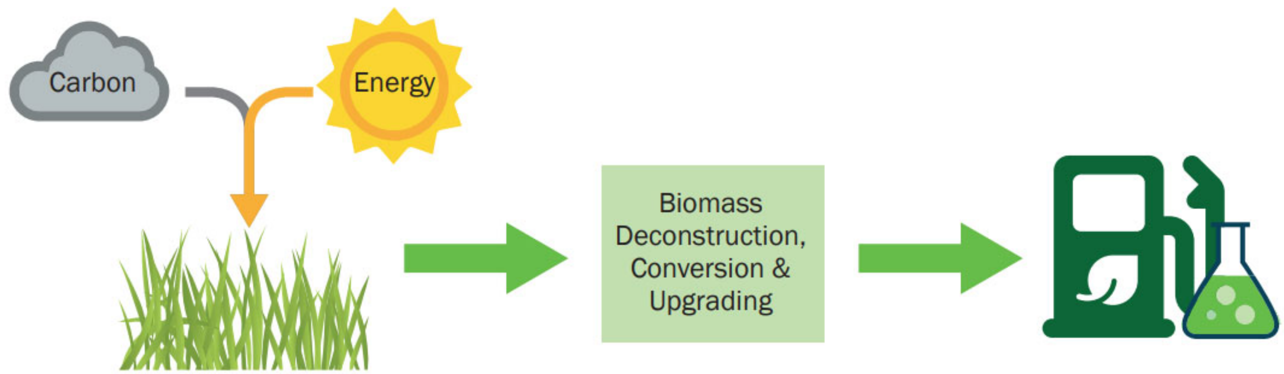
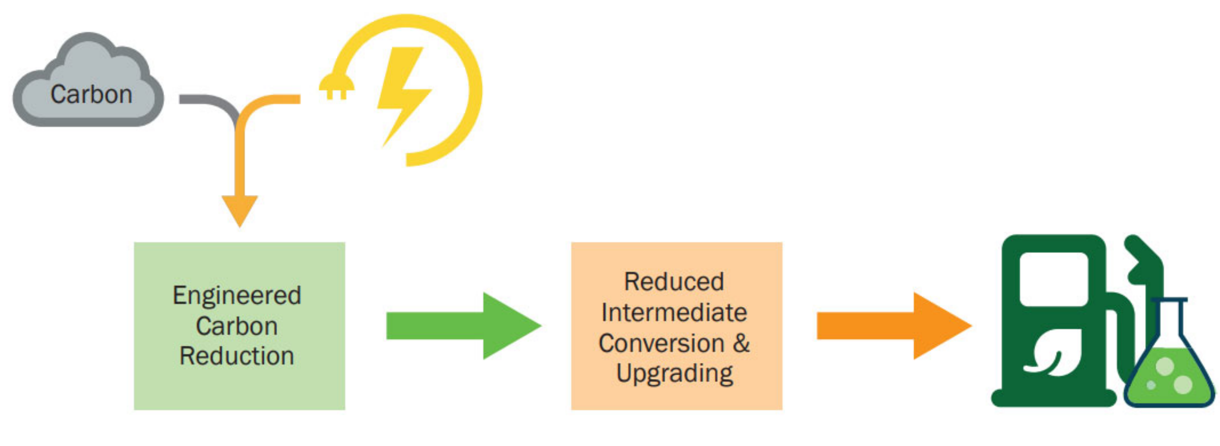
CO2-to-Fuels approach in EERE

Conventional biofuels



E-fuels



CO_2 Reduction and Upgrading for E-fuels Consortium

CO2RUe
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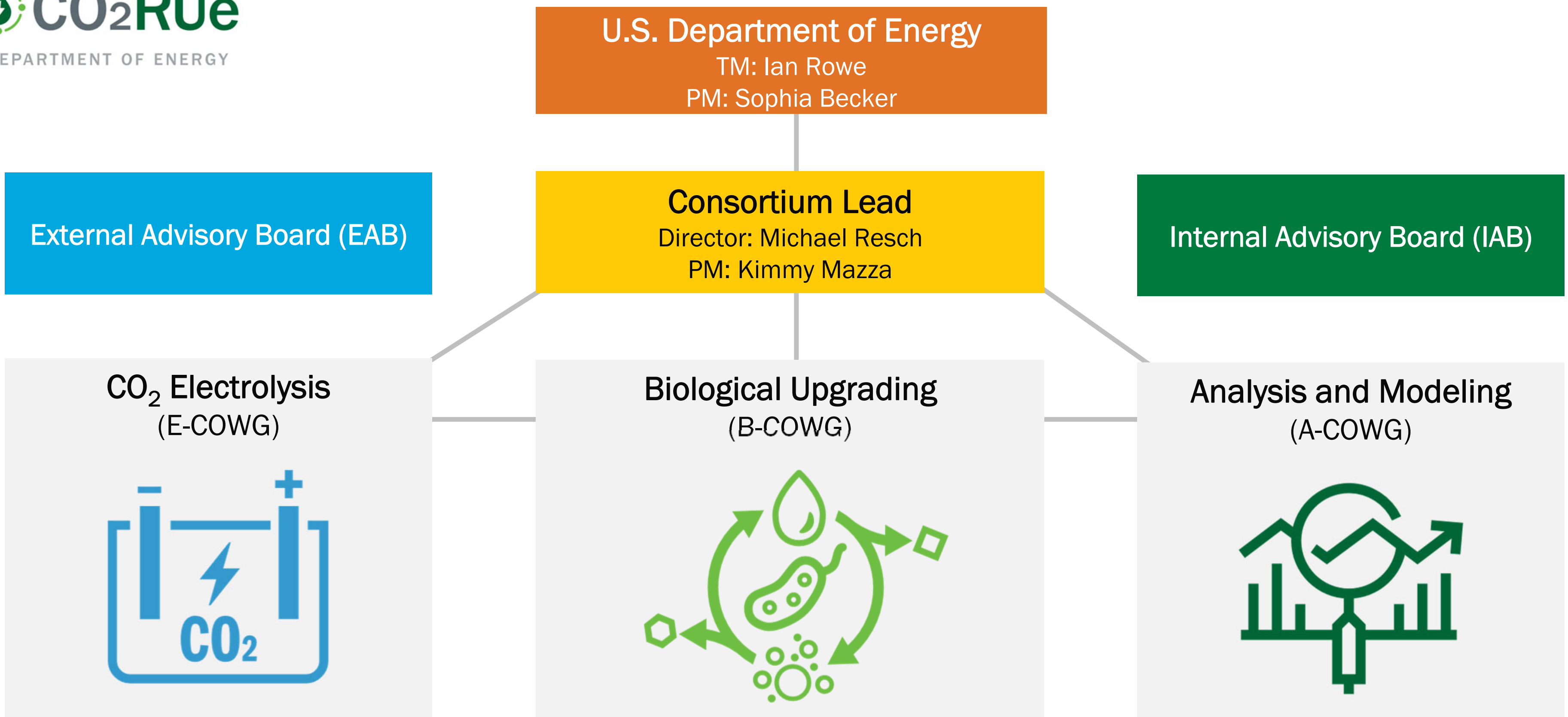

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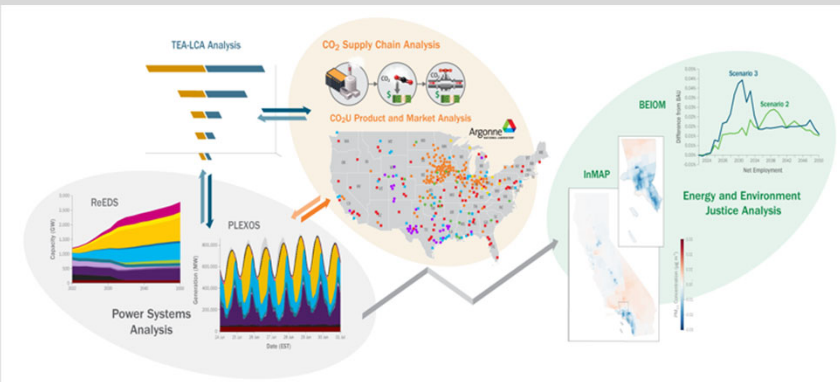
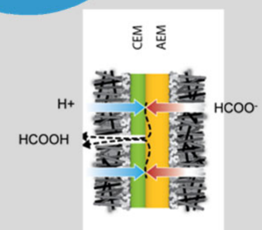
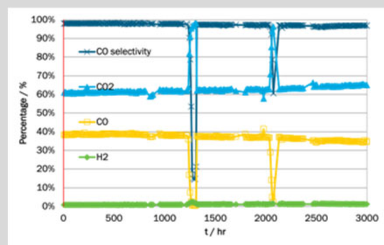
Consortium R&D efforts

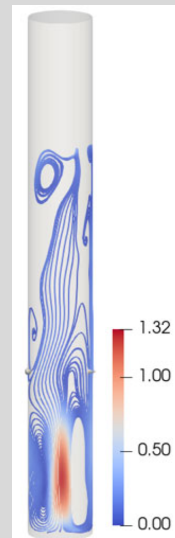


Identifying economic and environmental Drivers

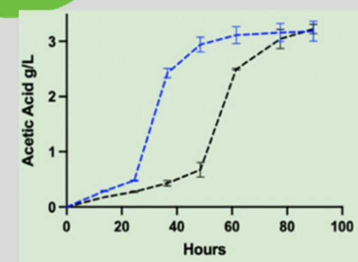


Electrolyzer design

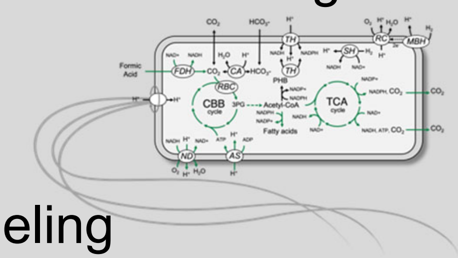




Reactor modeling



Metabolic engineering



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In progress: setting near term targets for enabling e-fuels

- **Feedstocks (siting, availability, cost)**
  - Low Carbon Electricity
  - CO_2
- **Electrochemcial**
  - Carbon efficiency
  - e^- efficiency
  - Scalability
  - Robustness
- **Fermentation**
  - T-R-Y
  - Carbon efficiency
  - Reactor design

Collaborative target setting with our Advisory Board:

Interested in participating in the Advisory Board? Contact us!

Final words

- E-fuels have solid potential for contributing to longer-term SAF goals
- There are almost as many e-fuels routes as there are biomass-derived fuel options. Some are theoretically ready for commercial scale, while many others are emerging
- E-fuels can be very low carbon intensity, however this relies heavily on access to massive amounts of dedicated renewable electricity deployment
- I welcome questions/comments!

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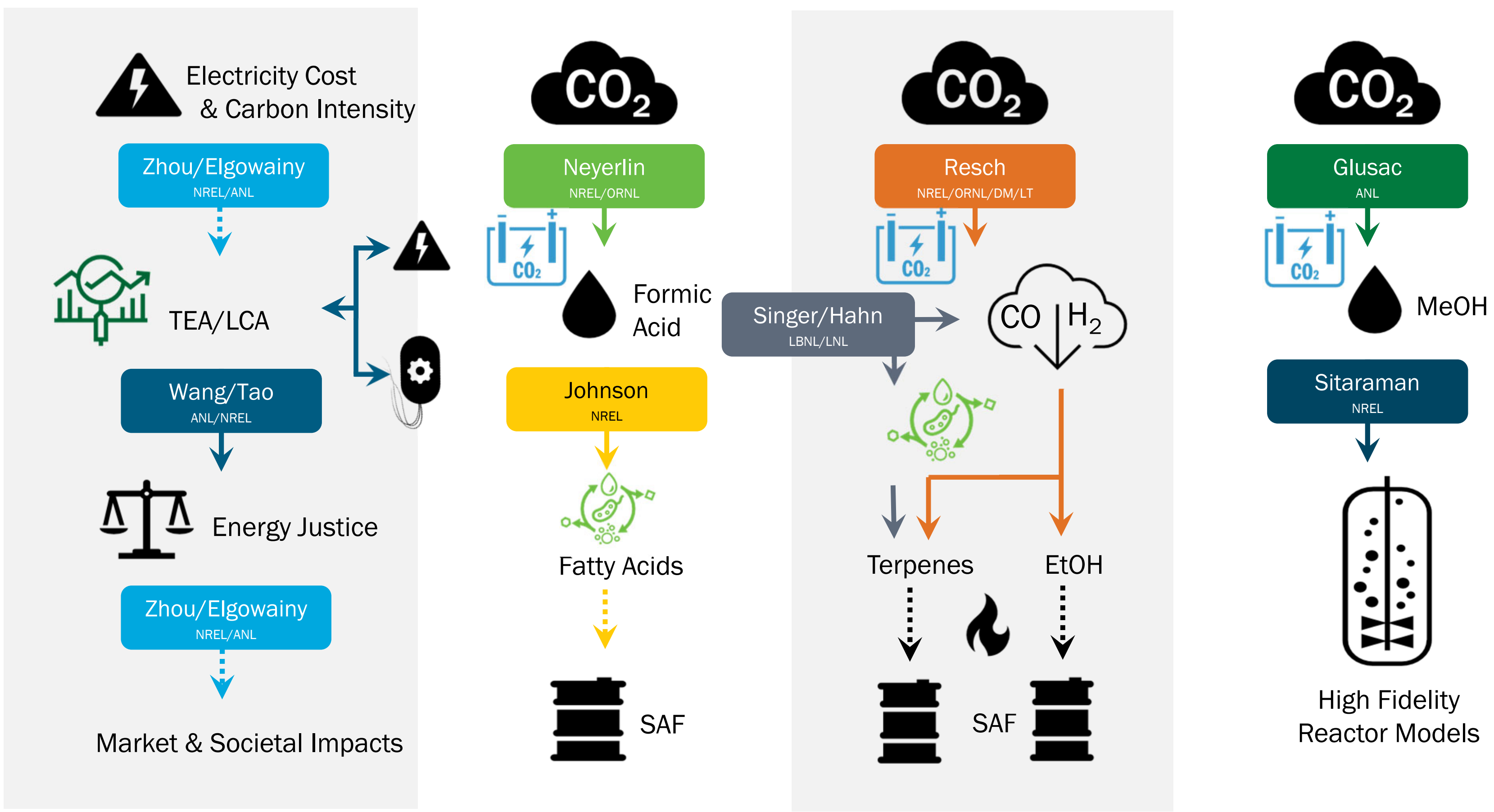
Consortium R&D efforts



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