CO_2 Reduction and Upgrading for e-Fuels Consortium

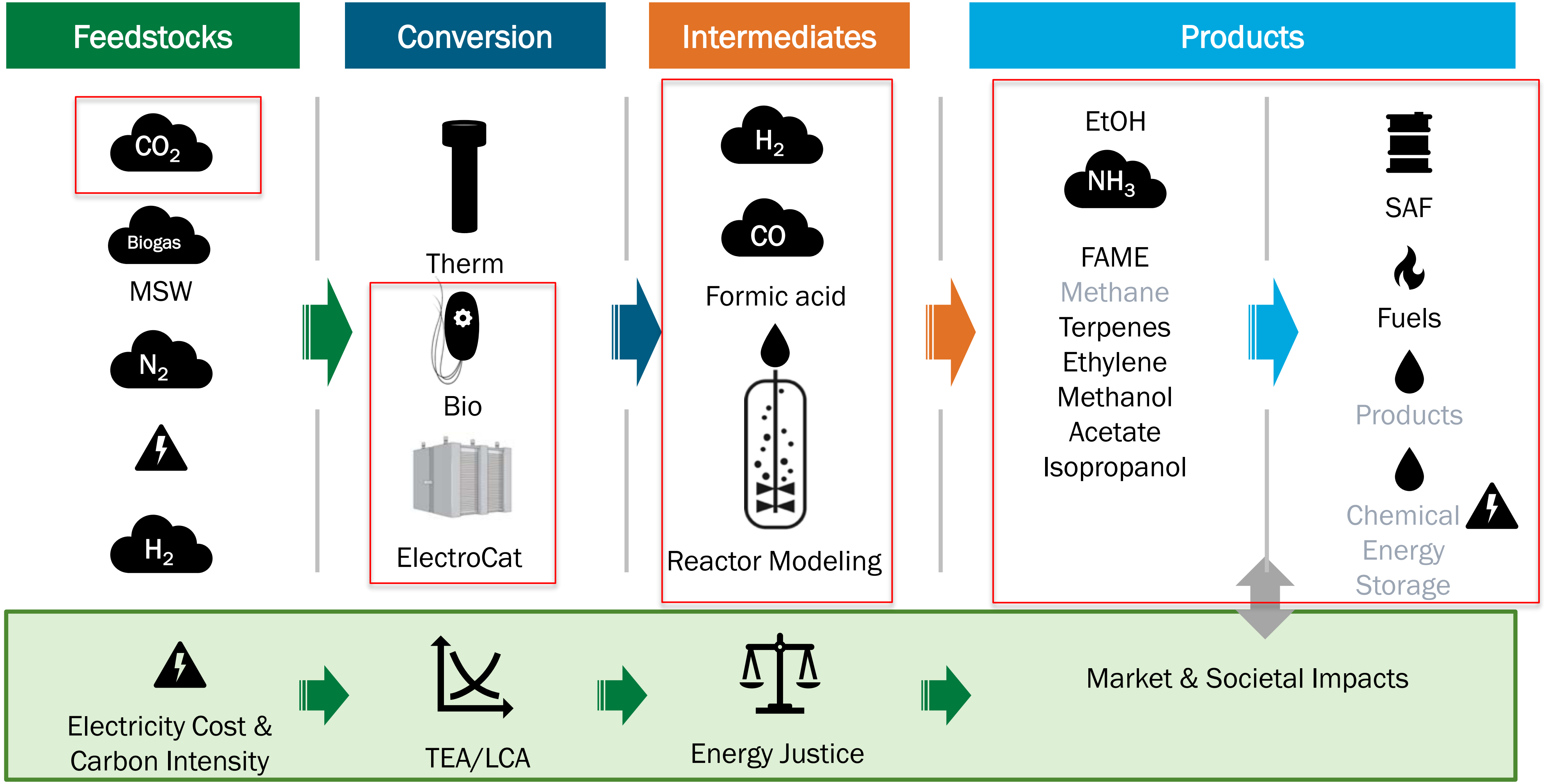
U.S. DEPARTMENT OF ENERGY

Combining CO_2 Electrolysis with Biological Upgrading to Fuels and Chemicals: Turning Waste into Fuels

Michael G. Resch – Director CO_2RUe

SIMB – 2024 SBFC

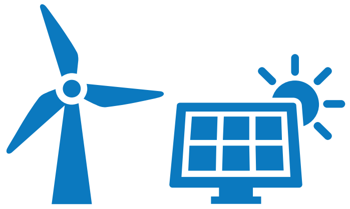
Waste Gas Research Areas



Opportunity and Costs For Inputs To PTL

Aviation Fuels
Marine Fuels
BECCS
Chemicals
Materials
Pellets
Steam

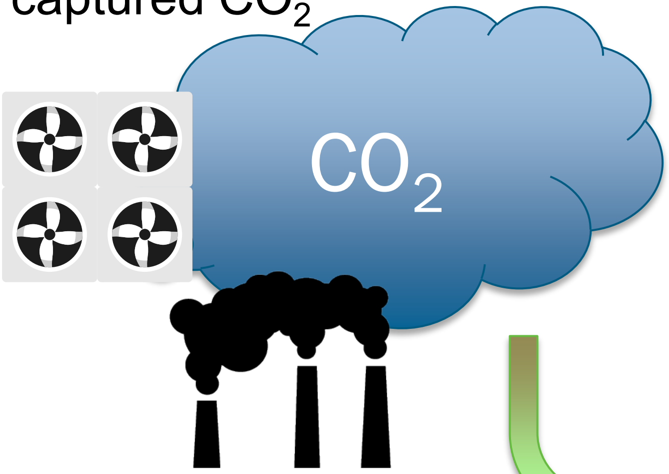
Biomass



Renewable Electricity

PTL
Grid decarbonization
EVs
Fuels
Hydrogen
Chemicals
Industrial decarbonization

In the long-term augment biomass with captured CO_2



Near Term:

- Improve carbon efficiency of biomass processes to reduce opportunity cost for biomass
- Reduce CI of existing biomass processes to enable deeper carbon draw-down

- Increase energy efficiency of PTL
  - Target should be ~ 50kWh/gal
- Learn how to do PTL at lower cost and lower CI
- Build out renewable electricity production

Renewable power

Long Term: PTL with captured CO_2

*slide provided by Zia Abdullah

Working Towards Energy Earth Shots

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Clean Fuels & Products™

- ≥50% hydrocarbon chemicals produced from sustainable carbon sources
- **>85% net reduction in GHG emissions** vs. fossil based sources by 2035
- >400 MMT of fuels and chemicals from clean carbon sources by 2050

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Carbon Negative™

- Removal of gigatons of CO_2 from the atmosphere
- Durably store it for less than **$100/ton** of net CO_2-equivalent.

CO_2RUe Approach

Develop technologies to upgrade CO_2 to fuels and chemicals in order to reduce GHG emissions as well as land and water use and incentivize decarbonization.

How We Work Together

U.S. Department of Energy
TM:Robert Natelson
Sonia Hammache
PM: Sophia Becker

External Advisory Board (EAB)

Consortium Lead
Director: Michael Resch
PM: Kimmy Mazza

Internal Advisory Board (IAB)

CO_2 Electrolysis
(E-COWG)

Biological Upgrading
(B-COWG)

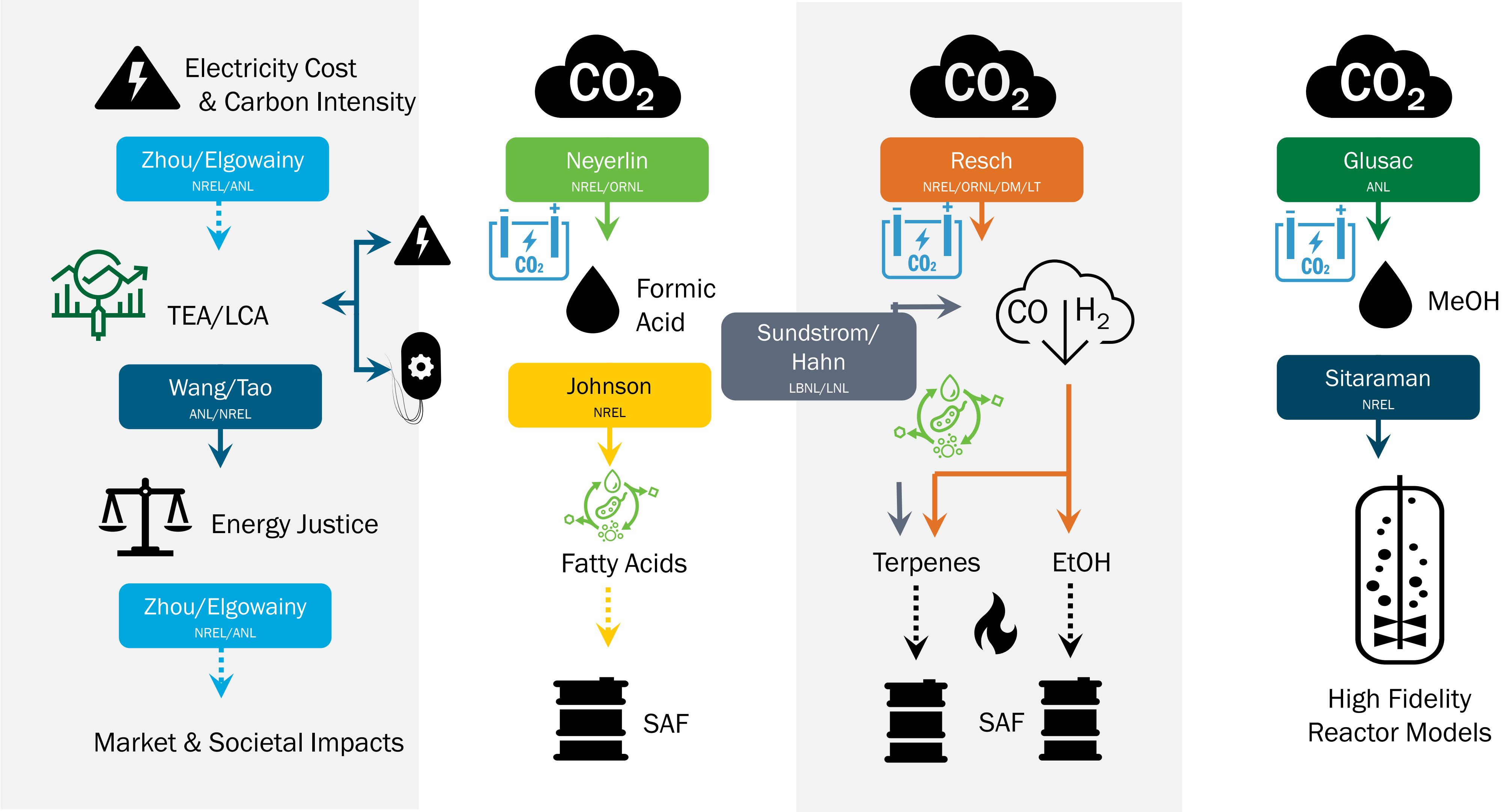
Analysis and Modeling
(A-COWG)

(COWG) CO2 Working Group

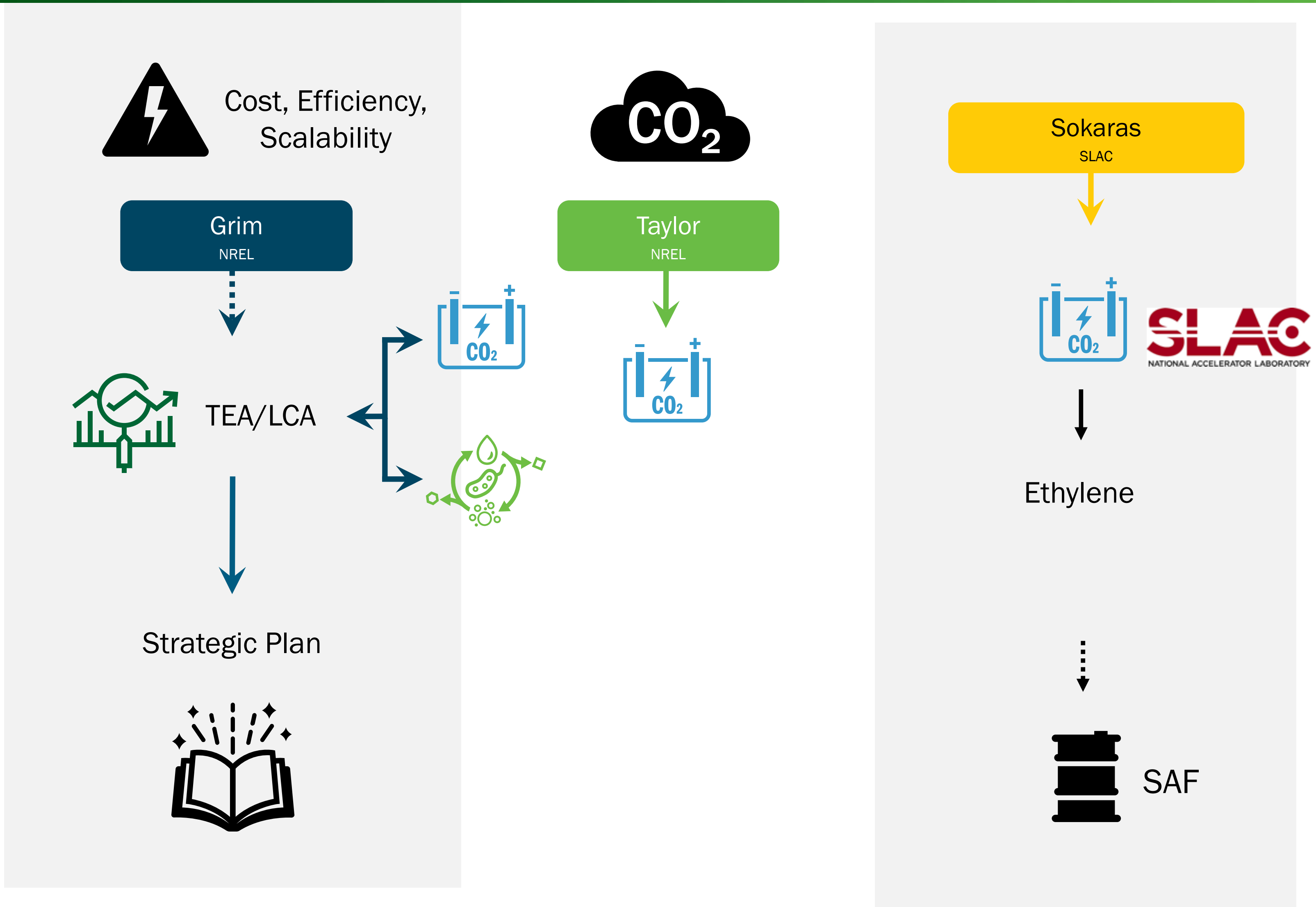
Lab Capabilities

Analysis and Modeling
Electrochemical
Thermochemical
Biological
Process Integration
Manufacturing
Product Analysis
Catalyst Development
Technology Scaling
Material Analysis

FY24 Projects



FY24 Seed Projects



Emerging Opportunities Involving CO_2

H_2-mediated Conversion Technologies

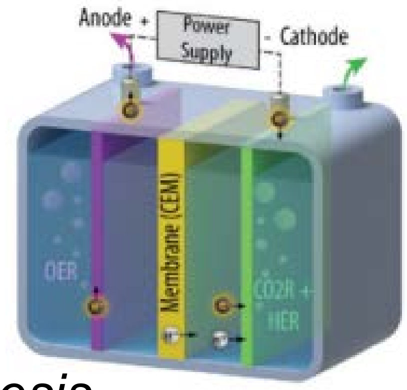
$CO_2 + H_2 \rightarrow CO + H_2O$
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

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

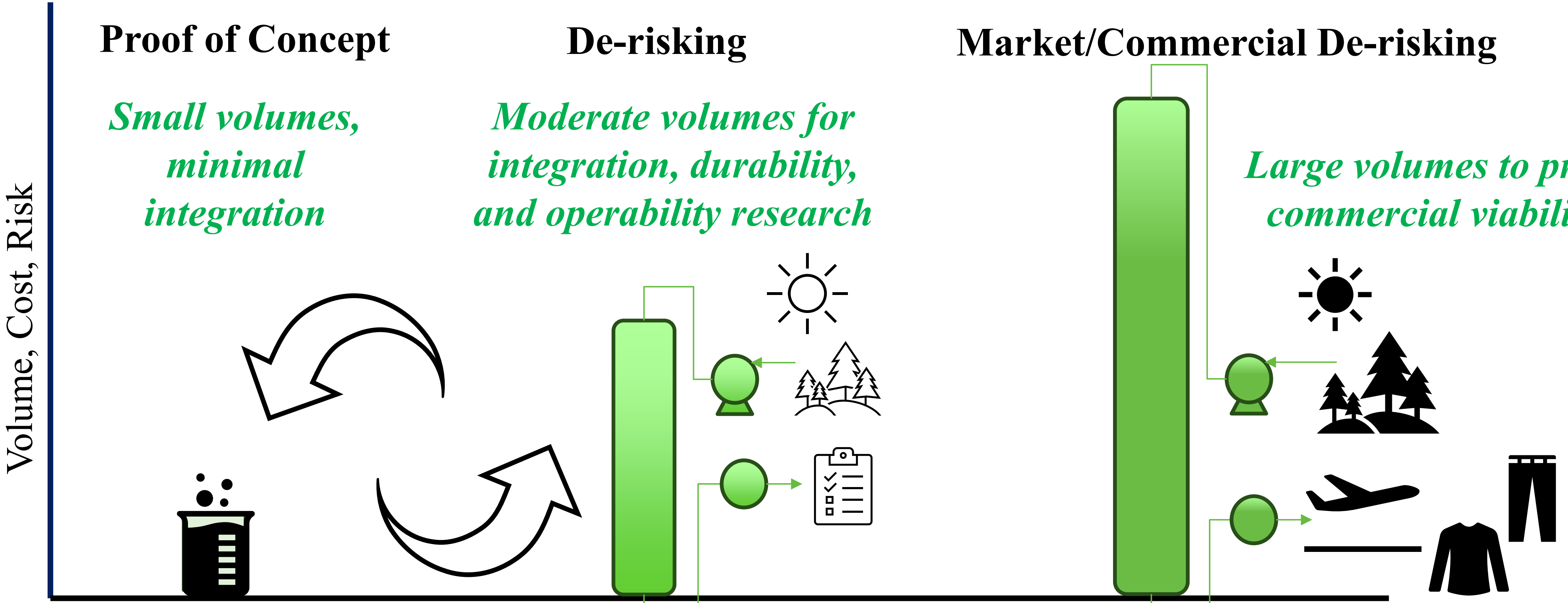
Microbial Electrosynthesis

↓Heat, ↓Pressure, ↓Scale, ↓TRL

Opportunity: *Emerging direct-electrification pathways show promising attributes, but low in TRL and in need of more R&D*

Slide by Gary Grim

Scaling and De-risking Strategy for e-Products



Bench Scale –
small volumes < 1 L per day

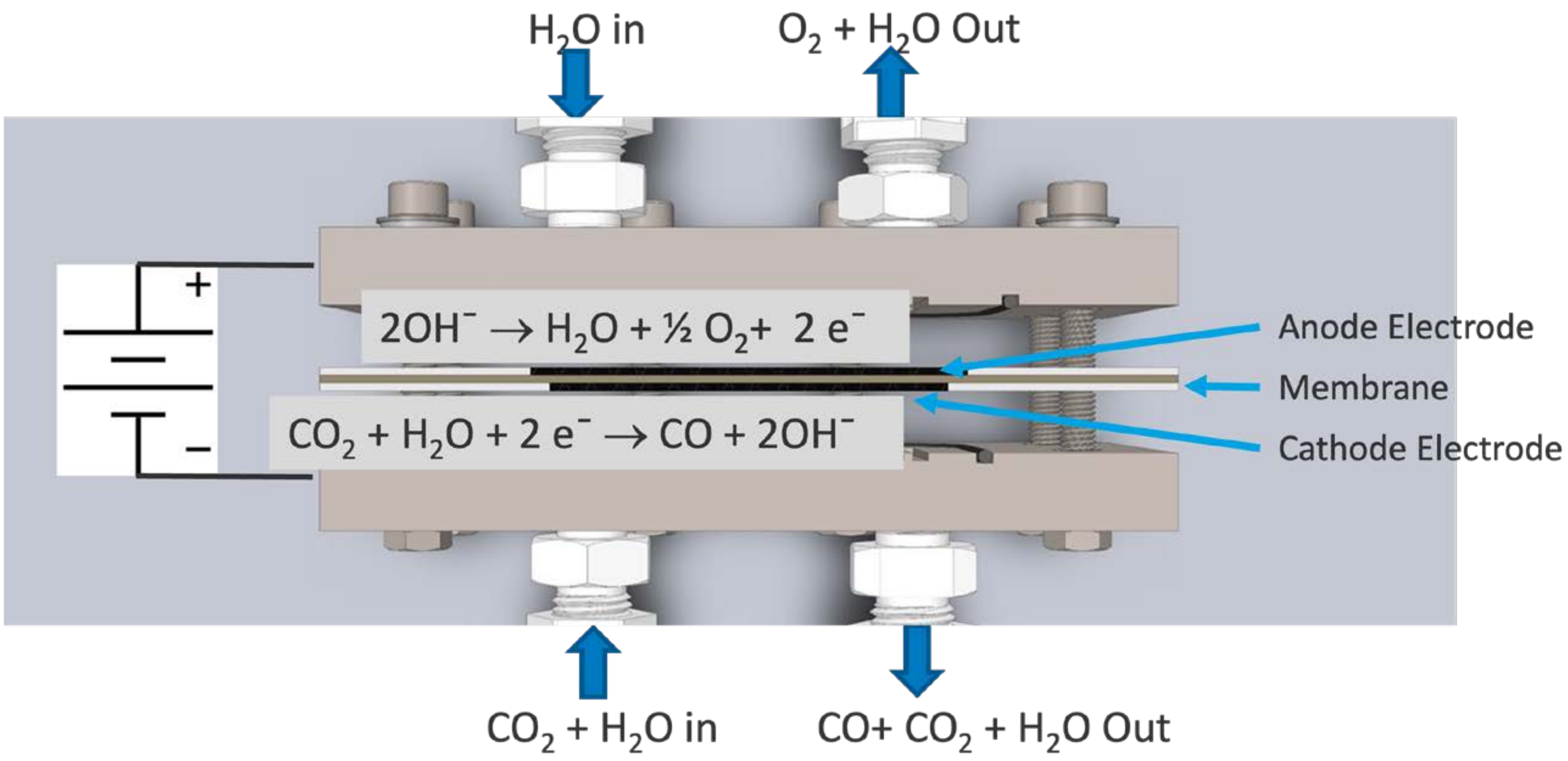
Integration Piloting –
Approx. 1 L to 1 gal per day
100 kW – 1 MW

Large Scale Piloting –
Approx. 1 gal to 1 barrel per day
1.25+ MW

OUT of SCOPE for CO_2RUe
Graduate Technologies to SDI

Slide provided by J. Schaidle
Business Sensitive

CO_2 Low Temperature Electrolysis

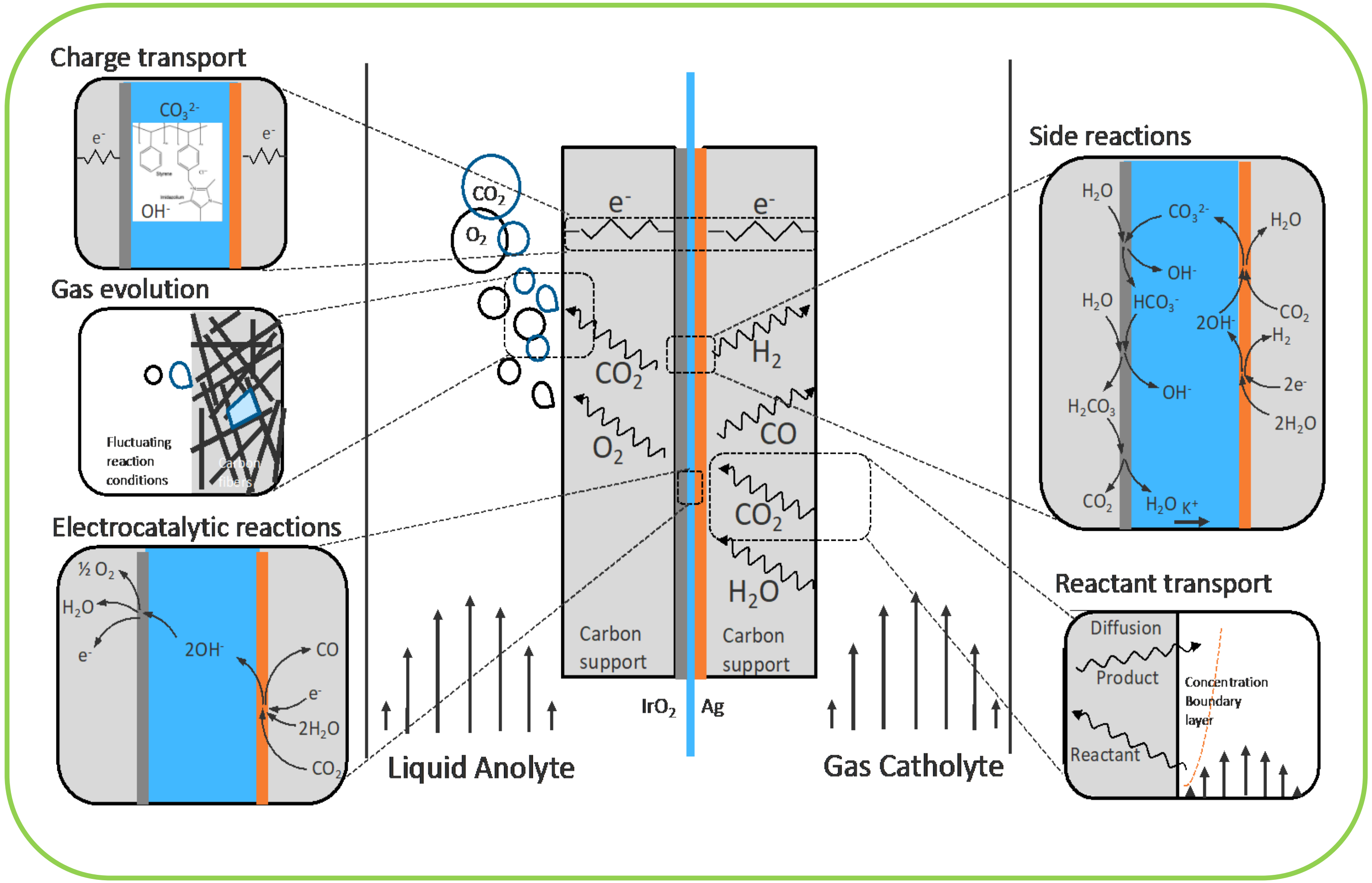


Prioritizing Electrochemical Failure Points & Technology Gaps

- Carbon support stability
- Heat management

- Carbon support chemistry
- Channel design

- Catalyst stability
- Contaminant tolerance



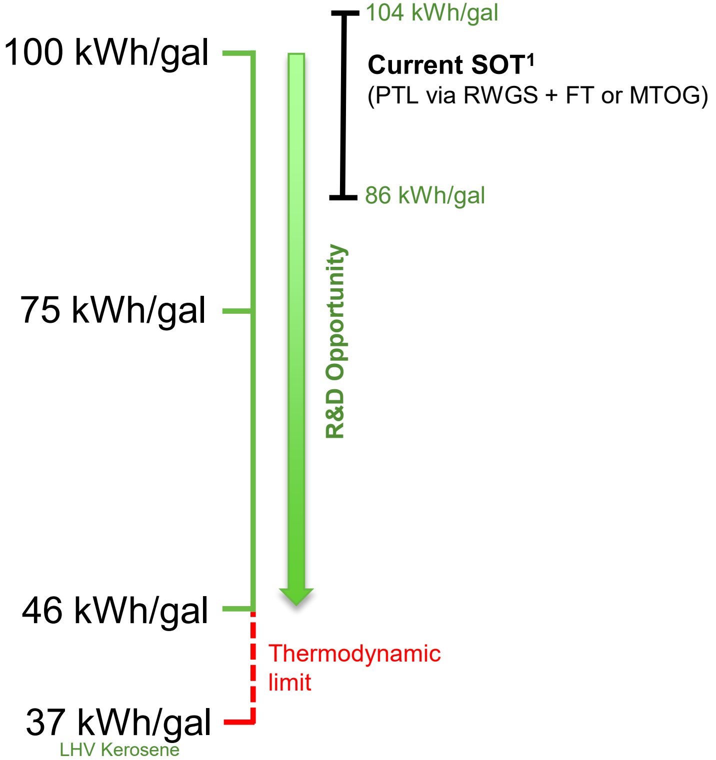
- Catalyst changes & deactivation
- Flooding
- Carbonate buildup

- Channel design
- Humidification requirement

- Realistic models for accurate scaling analysis

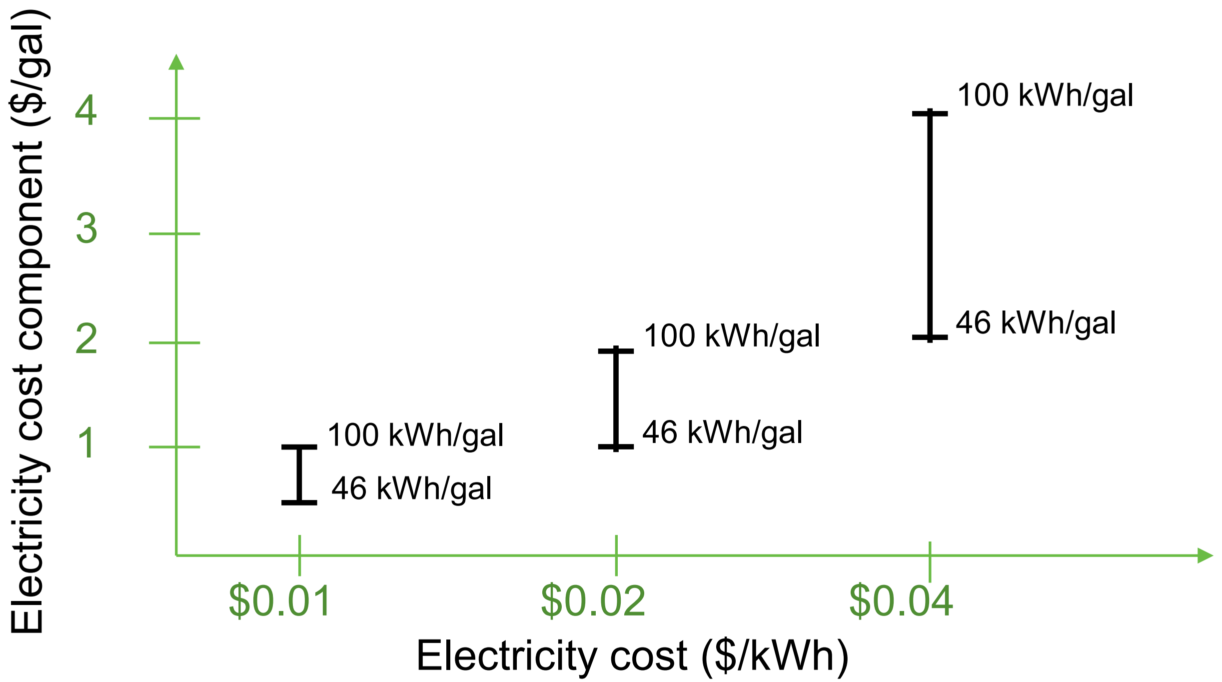
R&D Targets Will Focus on Energy Efficiency

Increase PTL Energy Efficiency

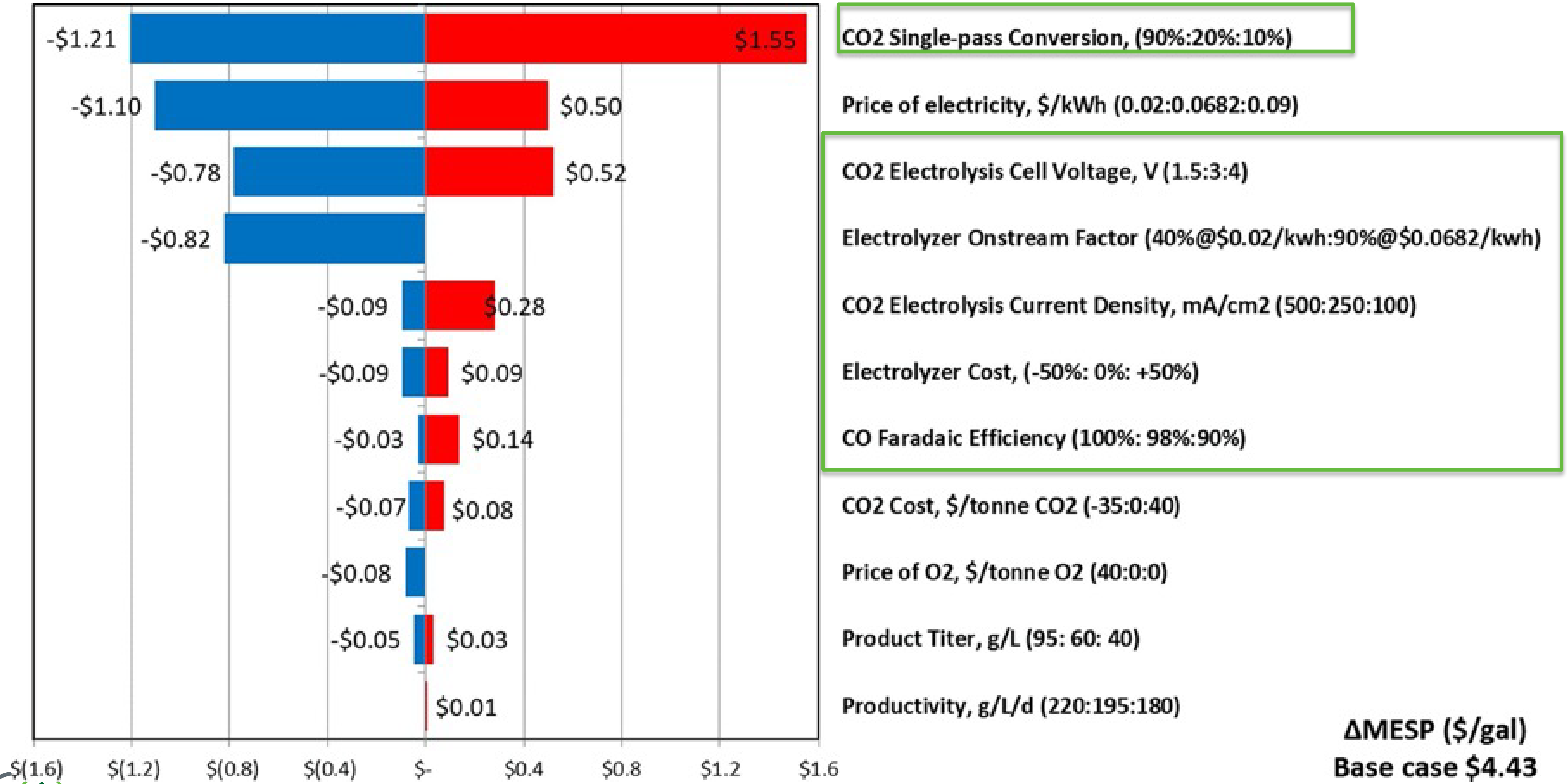


1:https://www.researchgate.net/publication/350955491_The_Road_to_Sustainable_Fuels_for_Zero-Emissions_Mobility_Status_of_and_Perspectives_for_Power-to-Liquids_PTL_Fuels

Energy Efficiency Has A Higher Impact At Higher Electricity Cost

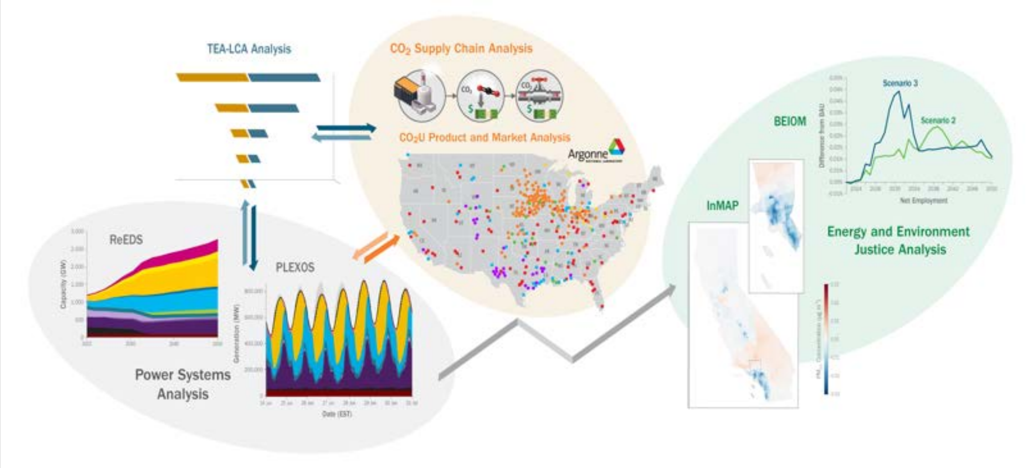


TEA of Bolt-On Process to Gen. 1 Biorefinery

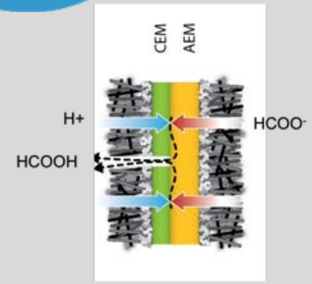


Huang *et al. Applied Energy* (2020)

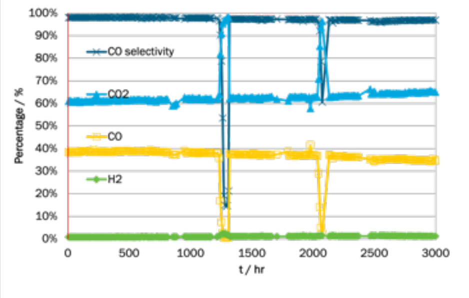
Technical Accomplishments

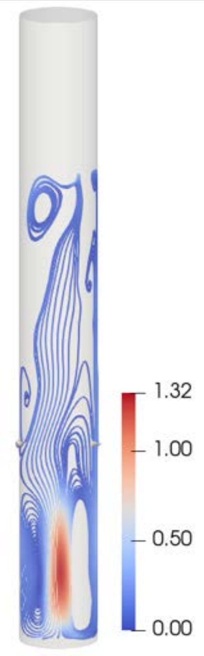


Identifying economic and environmental Drivers

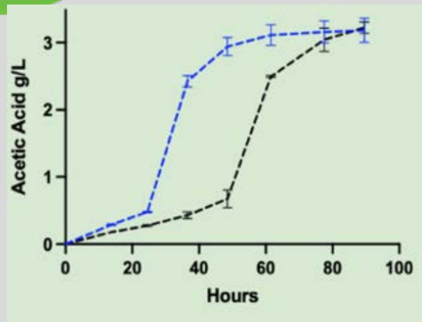


Electrolyzer design

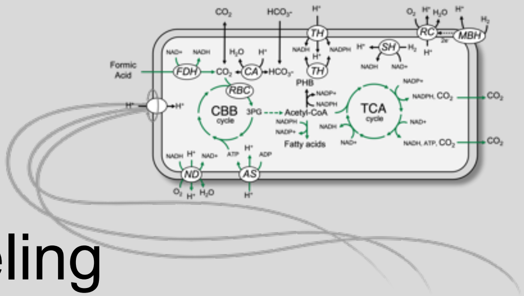




Reactor modeling



Metabolic engineering



High Level Accomplishments FY21-FY24

- **TEA and LCA of 12+** low and high TRL CO_2U pathways. Identified key cost and environmental drivers for industrial adoption. These findings will direct focus of technical targets.

- Determined the **US regional impacts** to local power grid costs (+6%), CO_2 supply, air and water quality, and employment if 20% (9.3 Bgal.) of the jet fuel production from conventional refineries are sourced from CO_2U technologies. Will leverage these results to identify near term opportunities to integrate CO_2U with Biorefineries.

- Demonstrated an integrated **CO_2 electrocatalysis → biocatalysis → ethanol** platform at lab scale. Informed carbon balance, durability, balance of plant and throughput capacity. Established lab scale demonstration to integrate multiple chemistries and intermediate conversion.

- **Integrated 2 - 3000 cm^2 electrolyzer stacks** with 1000L ethanol fermentation to convert up to 50 L/min of CO_2 into CO. Will leverage this capability to integrate materials and systems developed in the future consortium.

- **Released open-source CFD models** for simulating and optimizing CO_2 gas fermenters now being actively used by industry partners to improve reactor designs and improve gas mass transfer (LanzaTech, Electrochaea, Vowfoods)

- **Developed fully interactive LTE webtool** with user adjustable variables to rapidly screen how technical advances may impact the economics and carbon reduction potential of LTE CO_2 systems. This tool will be used to identify how technical work is "moving the needle" towards, energy/carbon efficiencies and capital costs/durability.

Biopower Project Overview

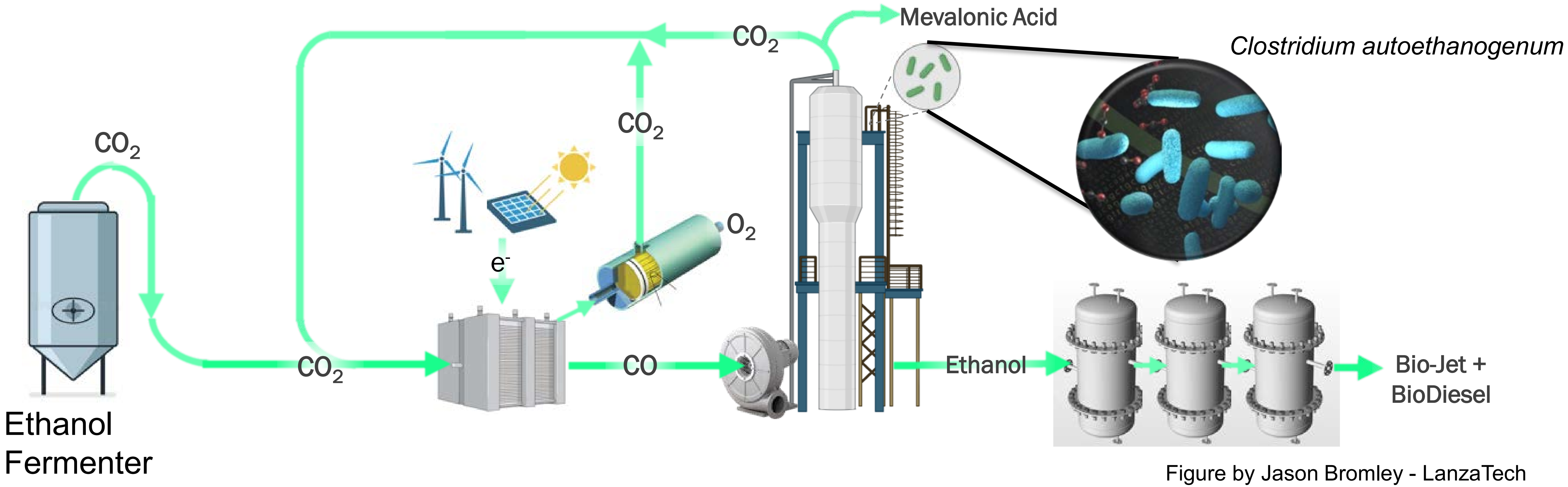
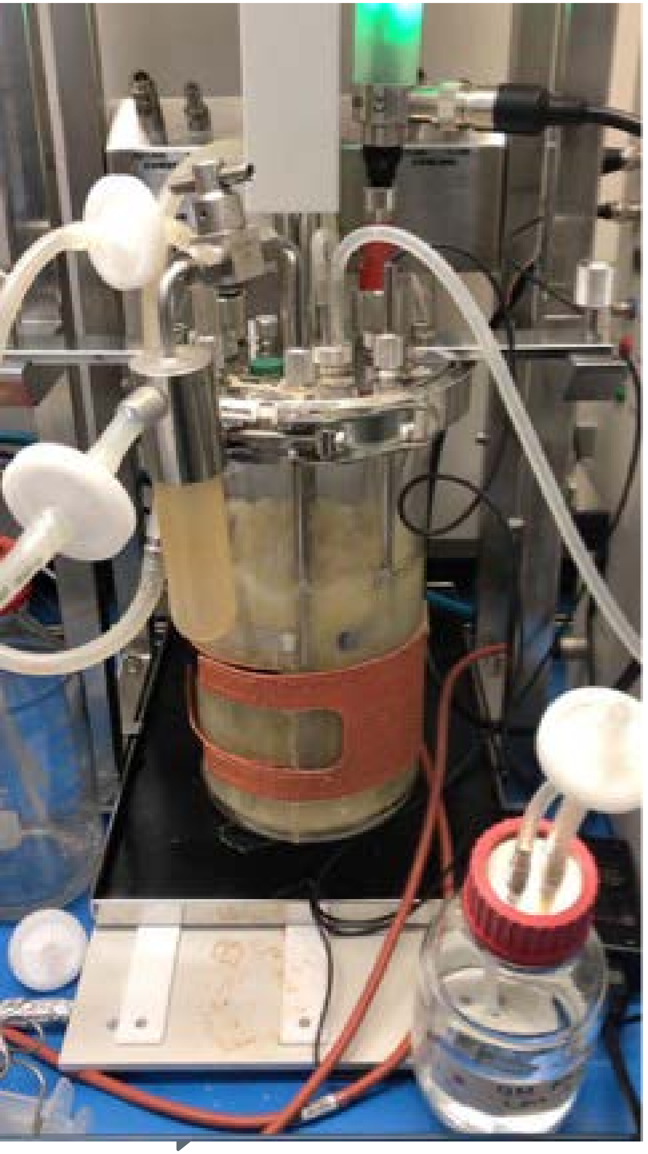


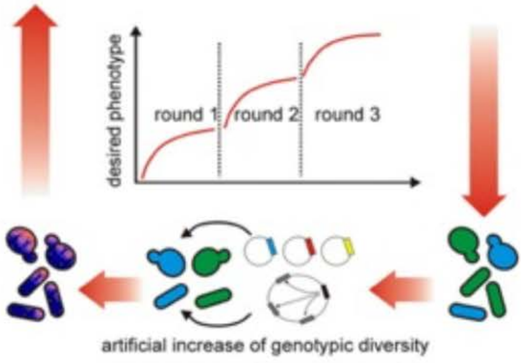
Figure by Jason Bromley - LanzaTech

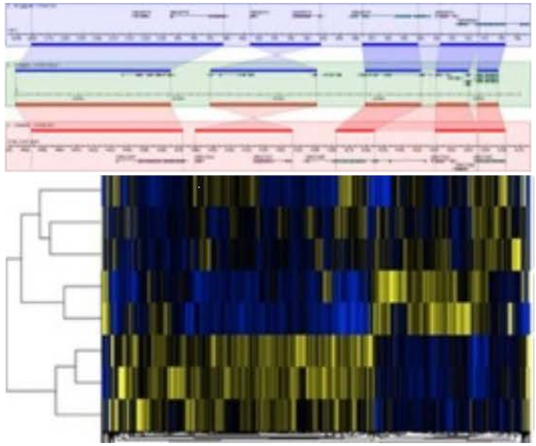
Strain Engineering Goals:

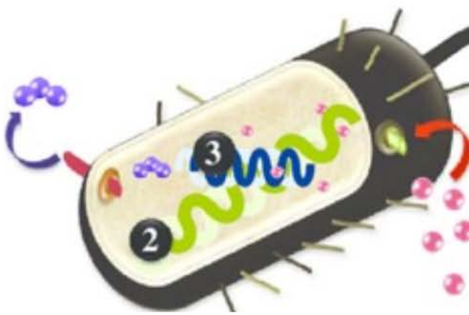
- Improve molecular biology tools and gas fermentation capacity in *Clostridium autoethanogenum*
- Evolve strains for enhanced cultivation on electro-derived gas streams via ALE
- Targeted engineering to enable high-yield EtOH/MVA co-production

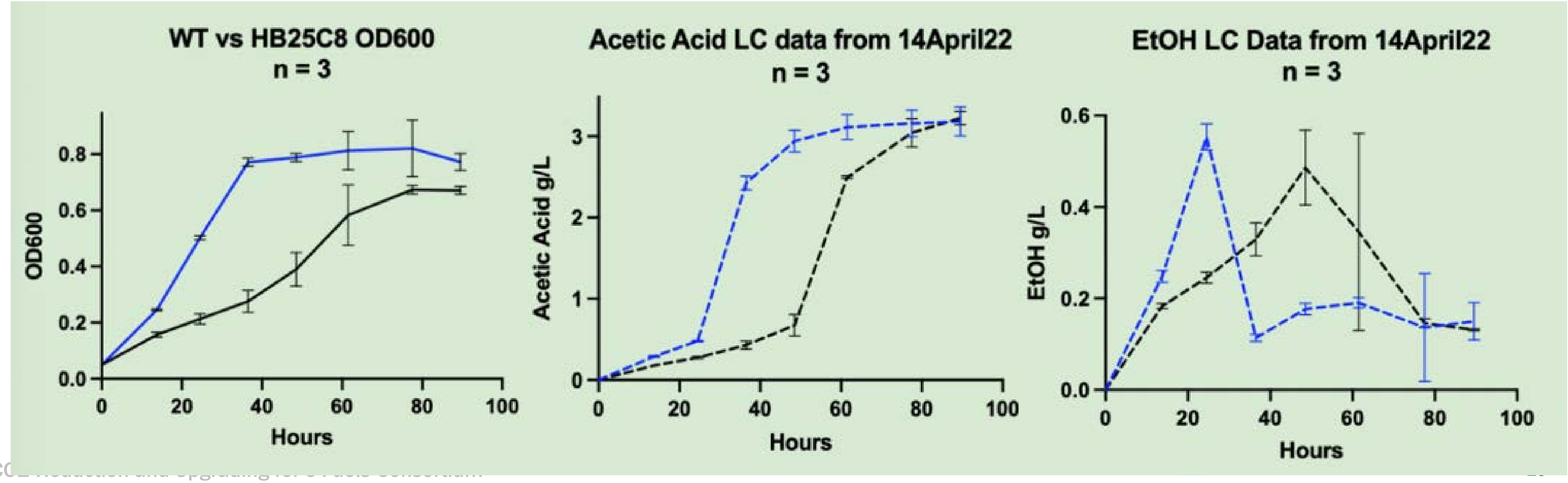
Adaptive Laboratory Evolution Enables Syngas Conversion



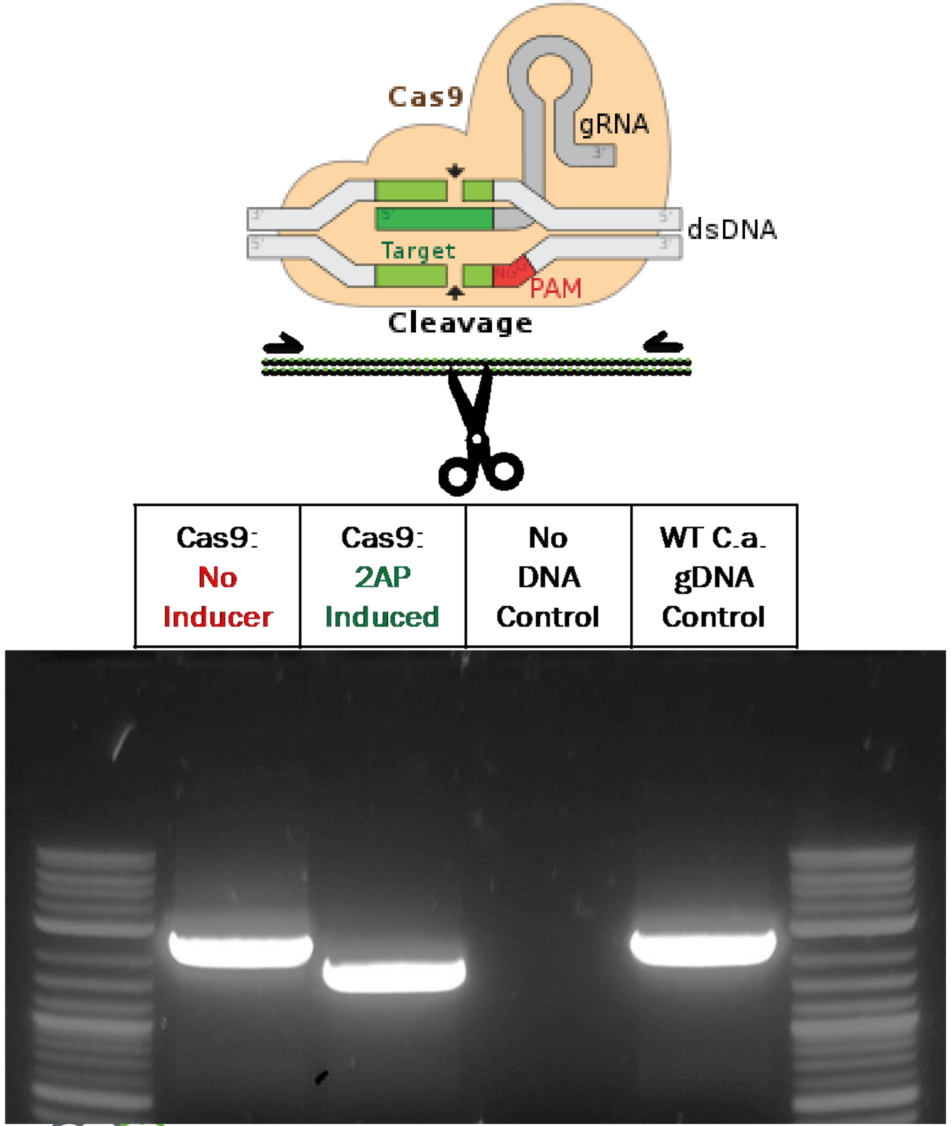


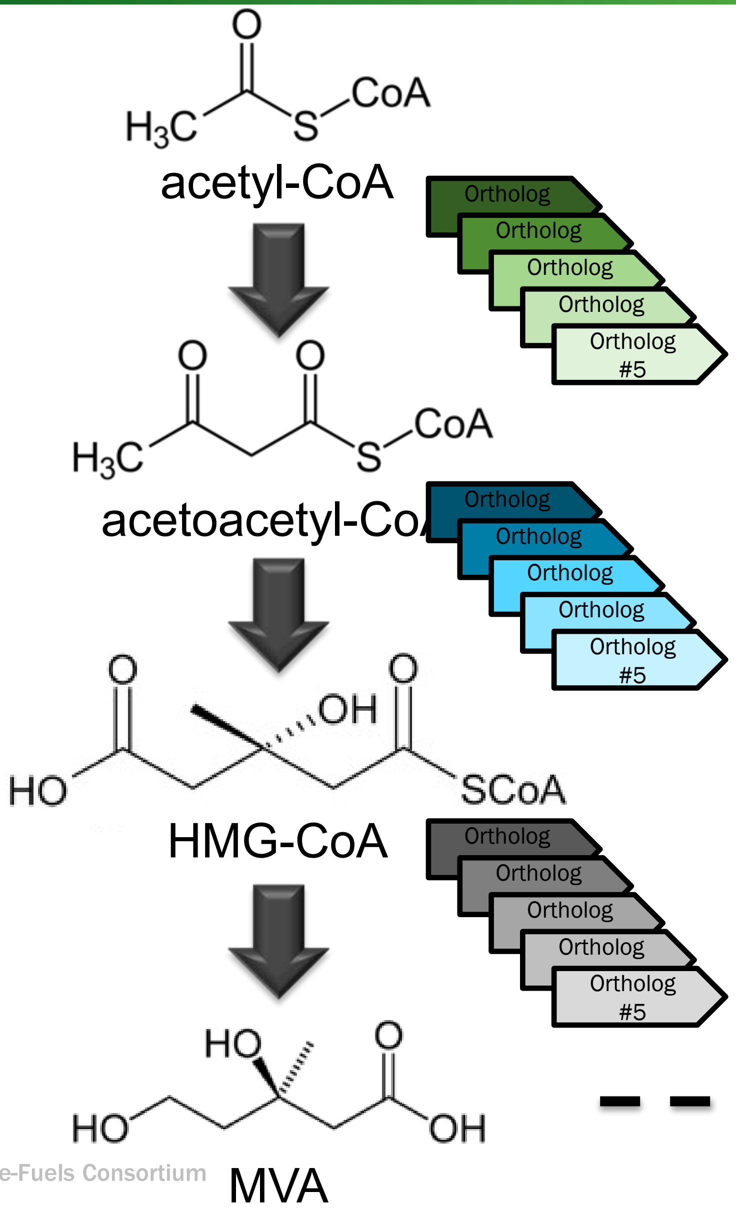


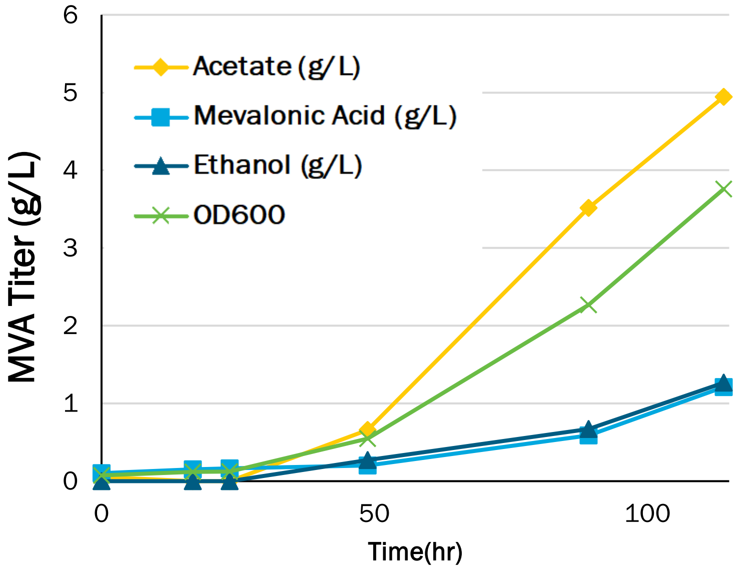


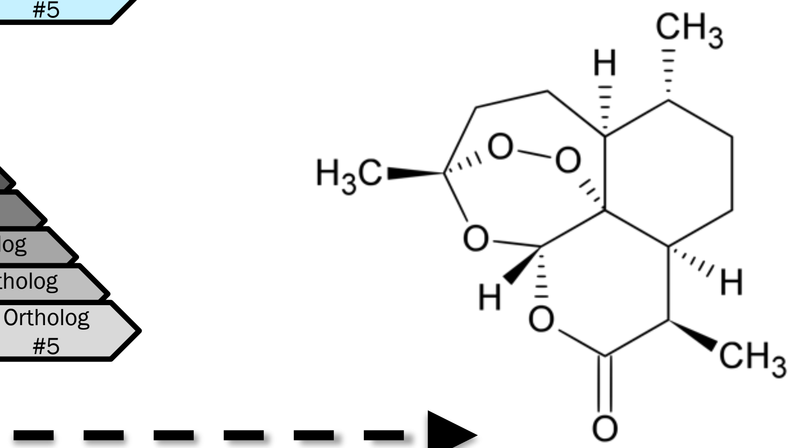


Targeted Strain Engineering Enables EtOH/MVA Co-Production



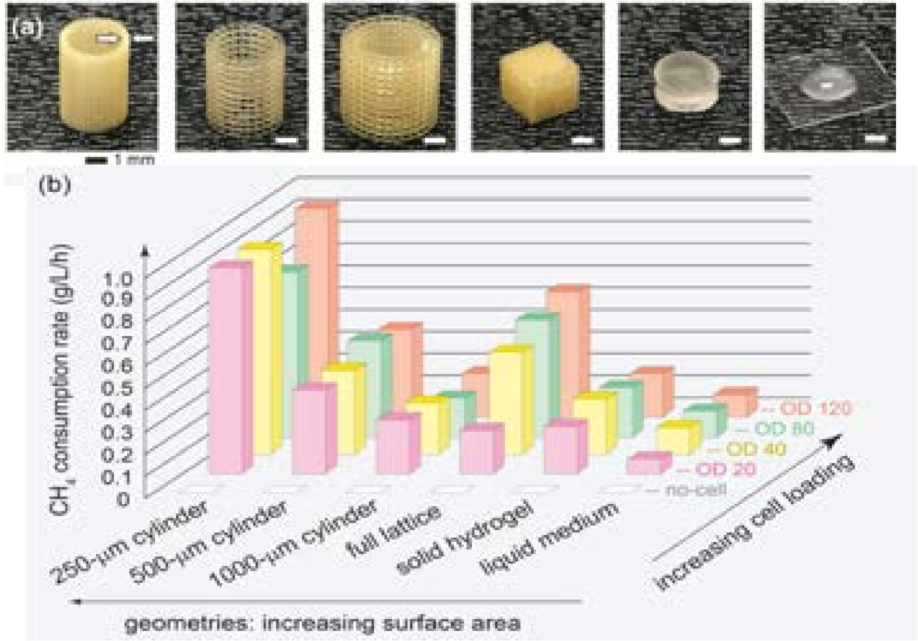






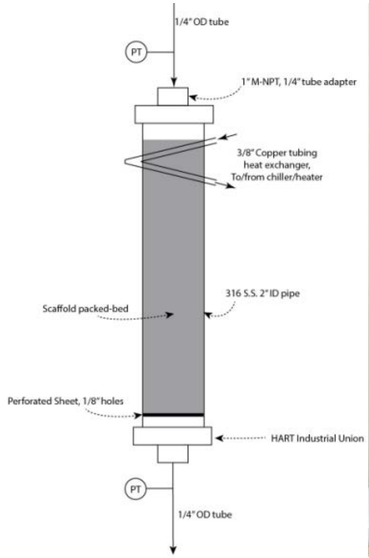
Terpene Co-Products

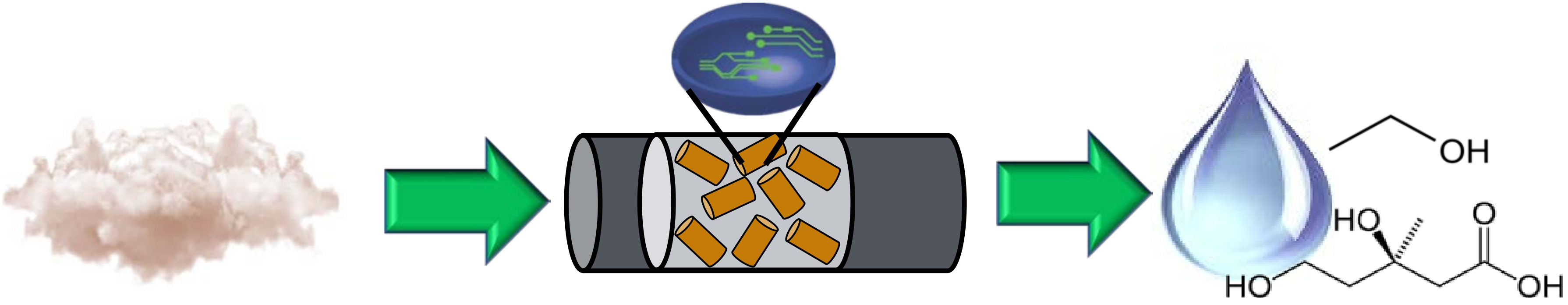
Immobilized Biocatalysis Enables Gas-to-Liquid Conversion



>10X Process Intensification Achieved

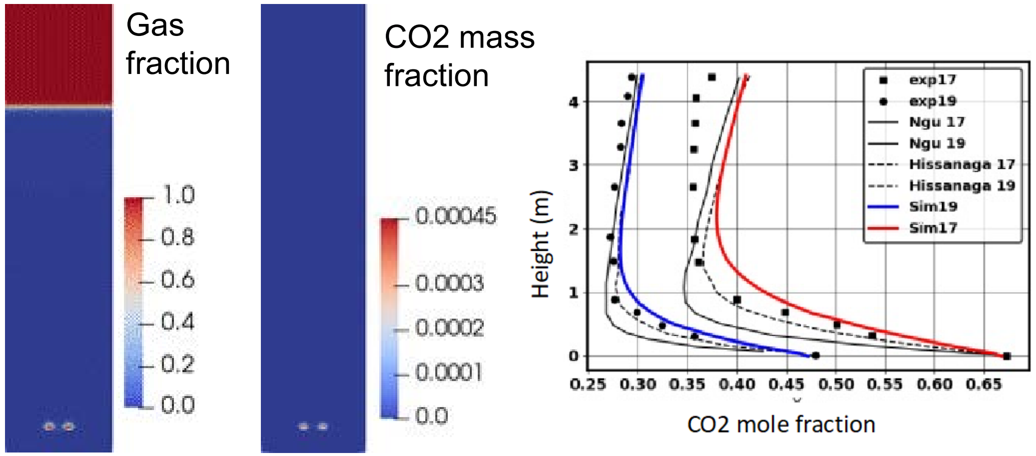
- Complete gas consumption in 24hr
- Ethanol Titer: 2.7 g/L
- Acetate Titer: 7.5 g/L



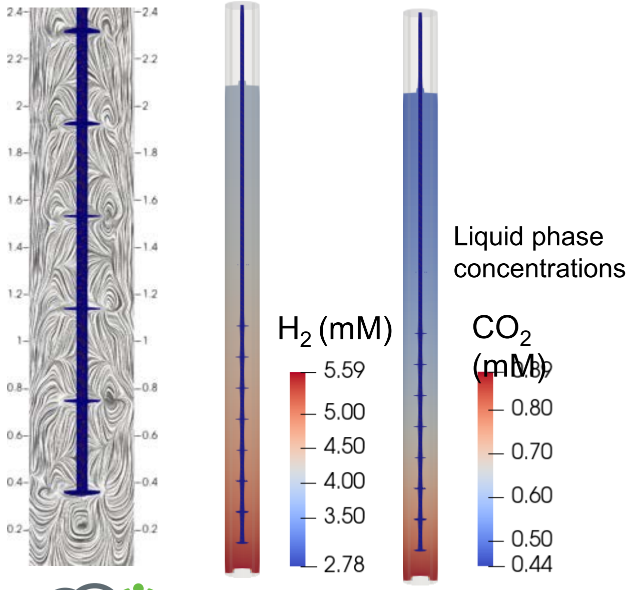


CFD Modeling Reactors to improve Mass Transfer

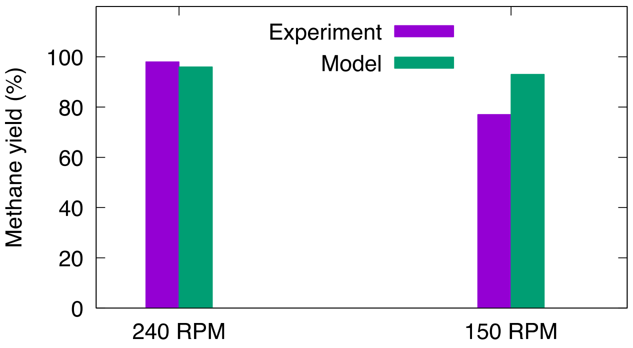
- Understand bubble distribution and coalescence
- Addressing mass transfer and heterogeneities are critical in large scale reactors
- Advancing current capabilities by:
    - Improved bubble size models for $CO_2/H_2/CO$ mixtures
    - Microbial reaction coupling with CFD

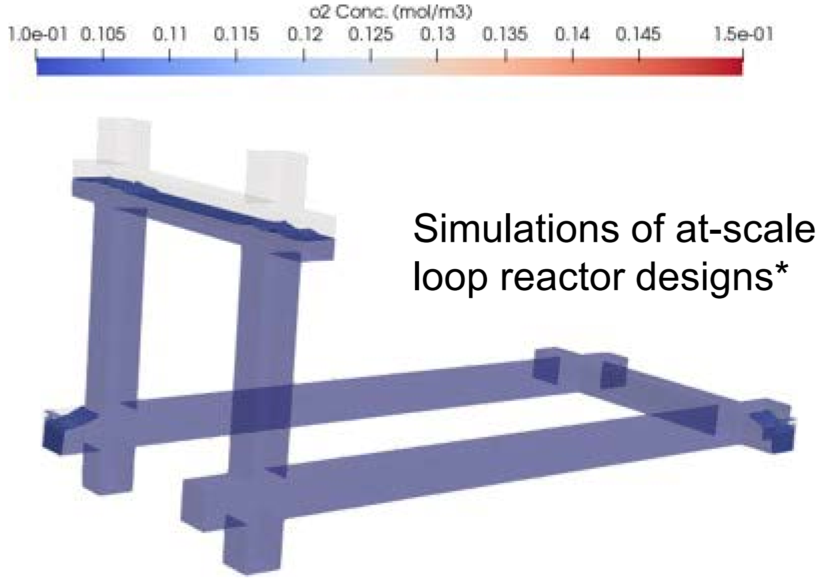


Validation of our models for bubble columns



Stir tank reactor simulation for NREL's 700 L biomethanation reactor



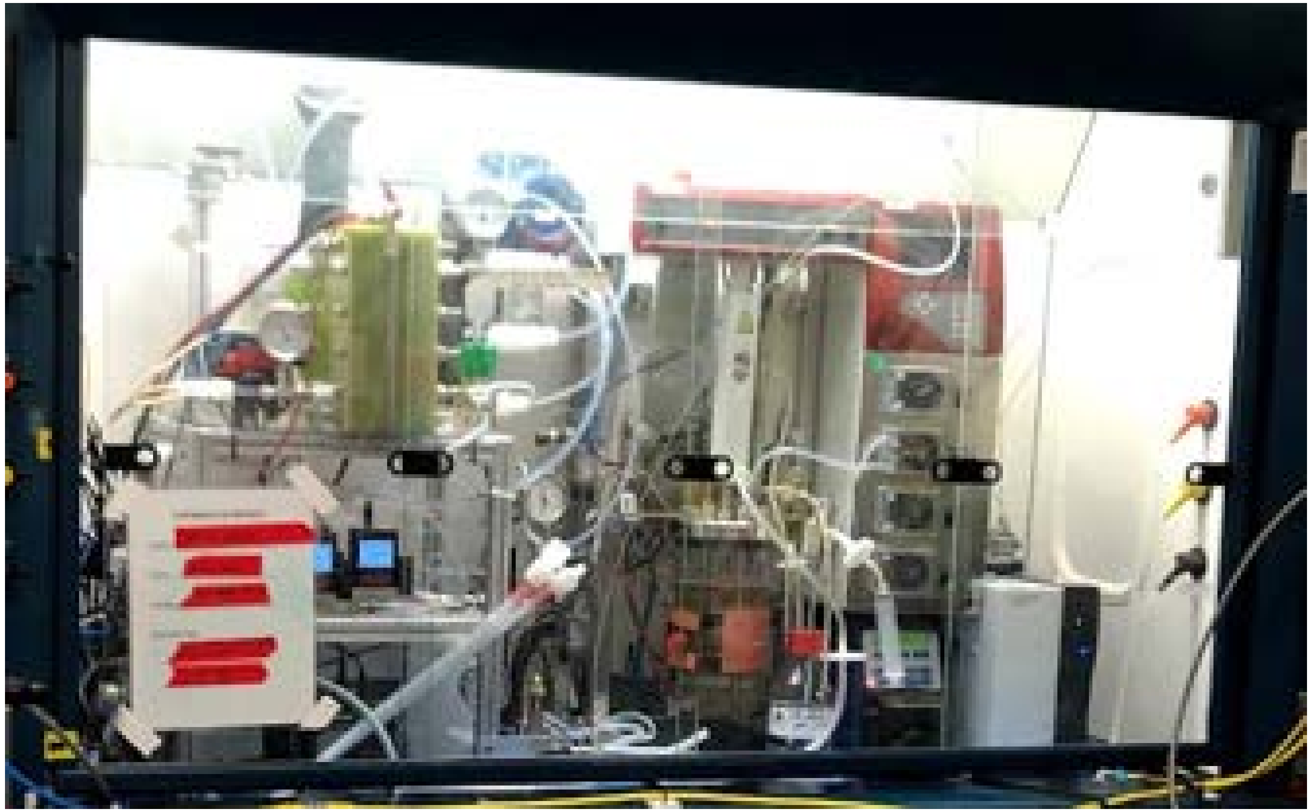


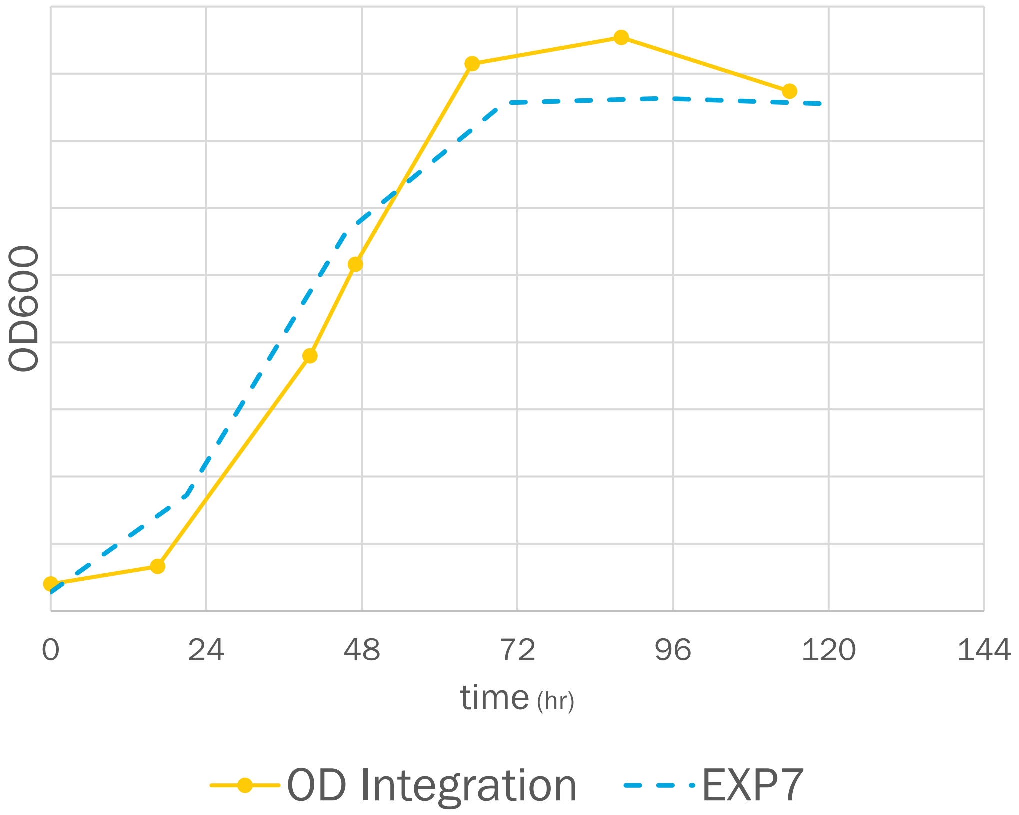
Simulations of at-scale loop reactor designs*

Hari Sitaraman (NREL)

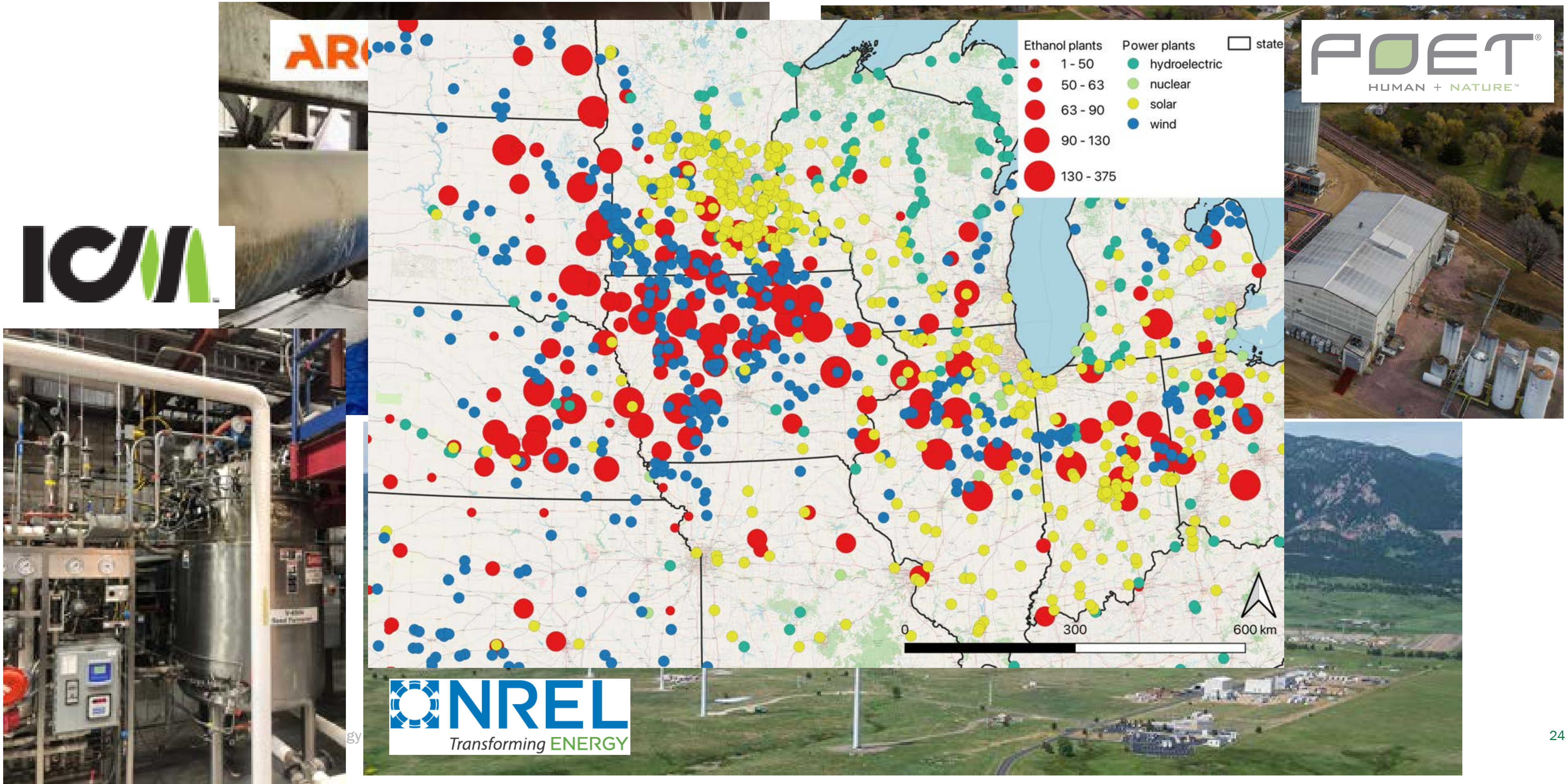
*Lackner et al., *Natural Gas—New Perspectives and Future Developments*., 2022)

Electrolyzer Integration with Gas Fermenter



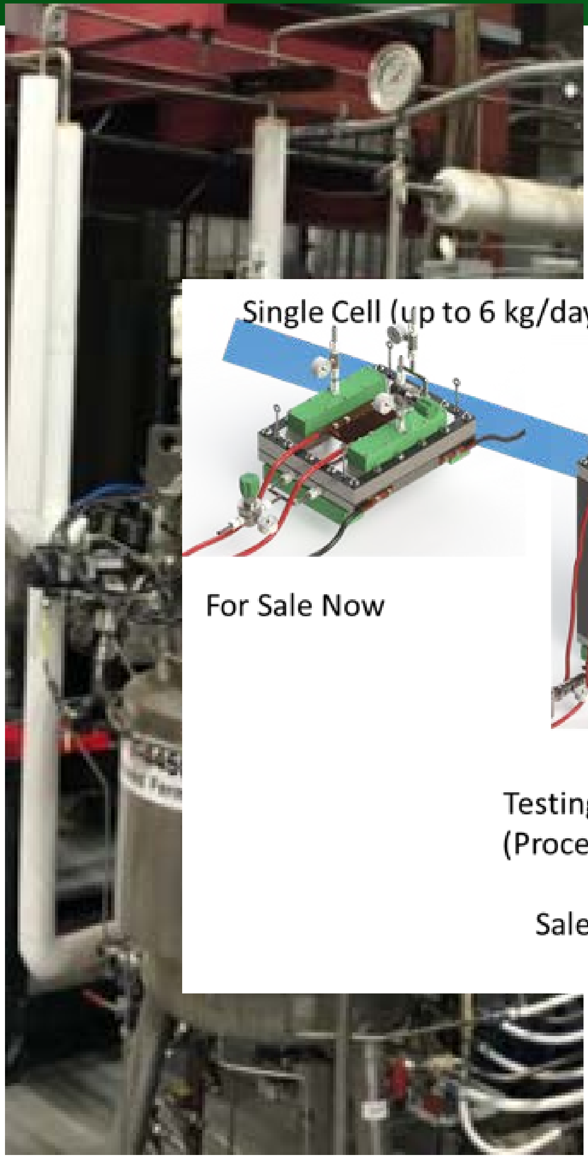


Industrial Flue Gas Feedstocks



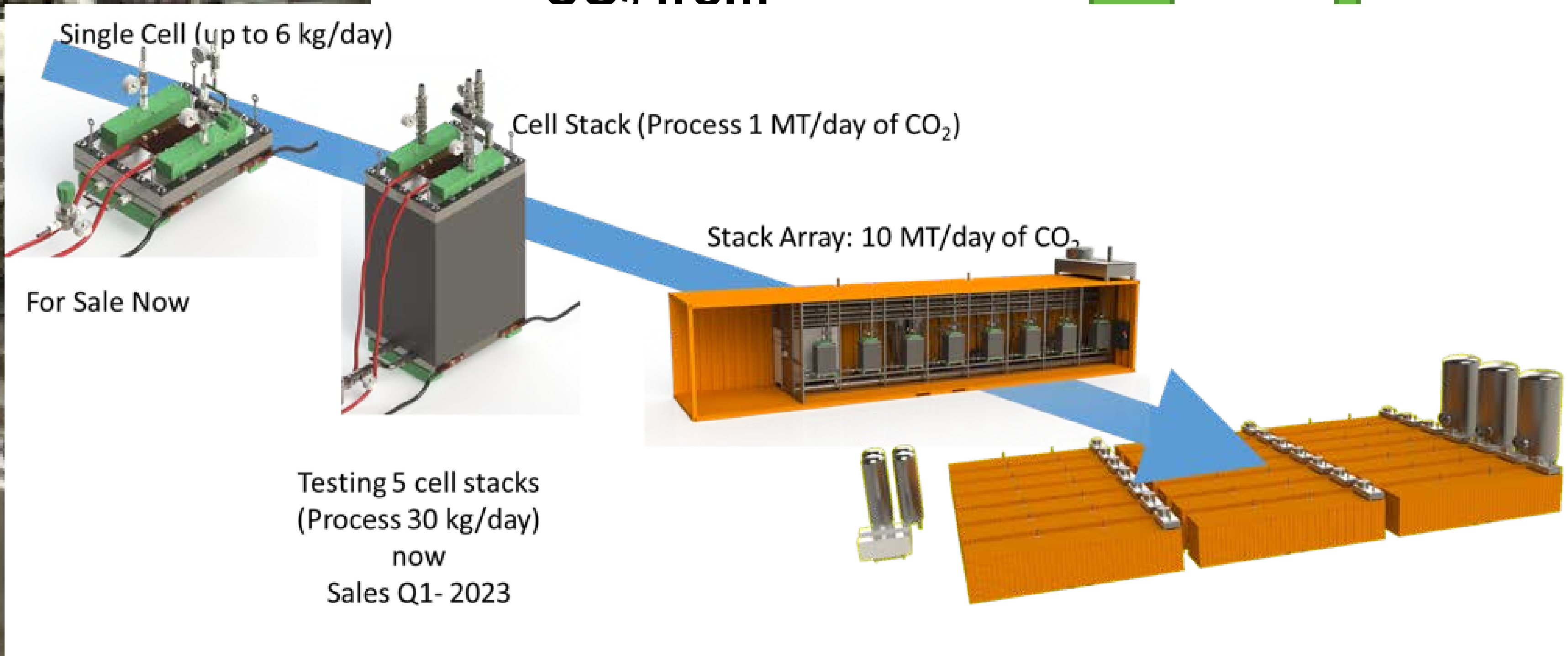
Integration and Scaling

1000L EtOH Fermenter

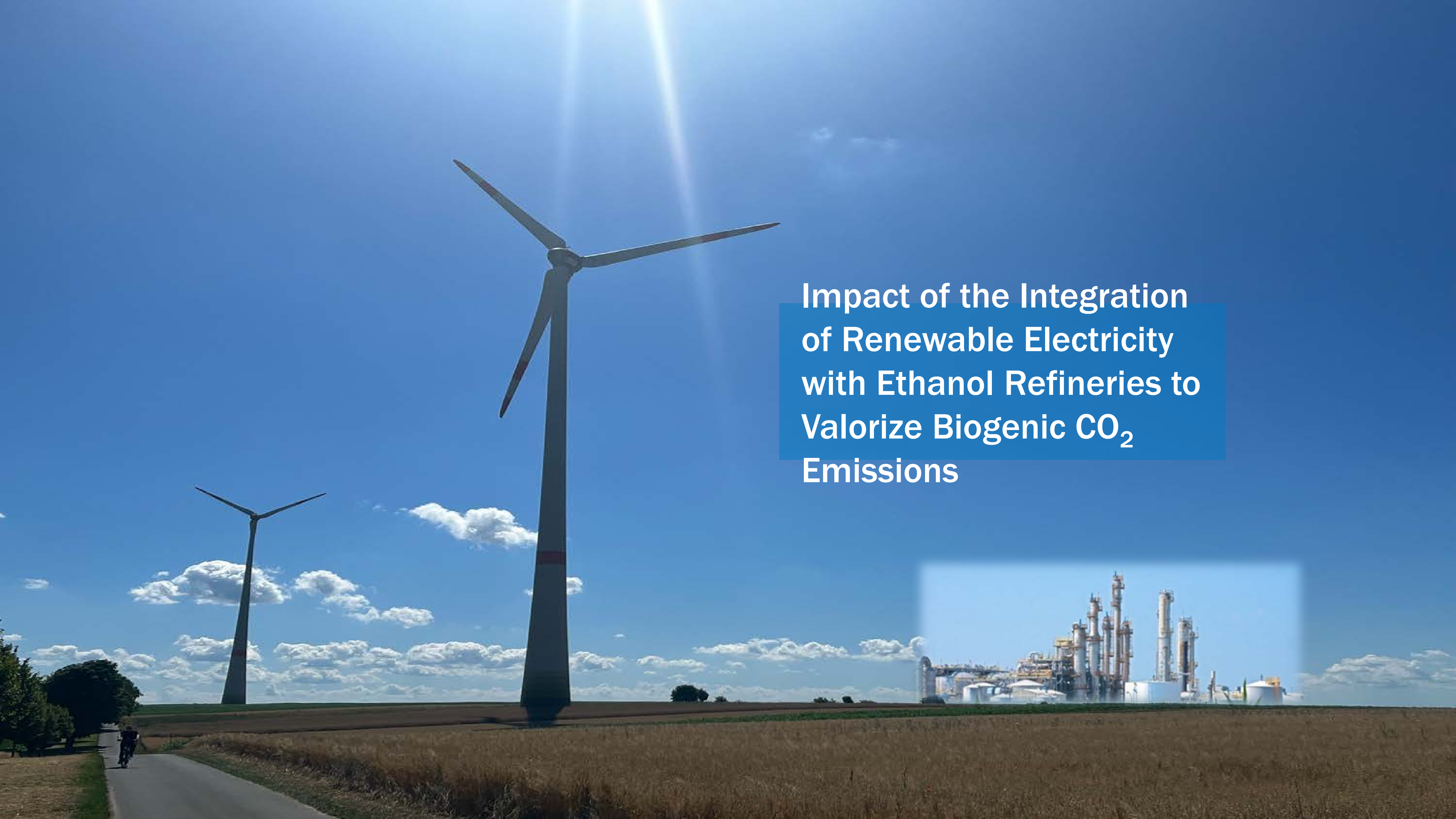


CO_2 from

$CO:H_2$



Cell Stacks of 1000
yzers



Impact of the Integration of Renewable Electricity with Ethanol Refineries to Valorize Biogenic CO_2 Emissions

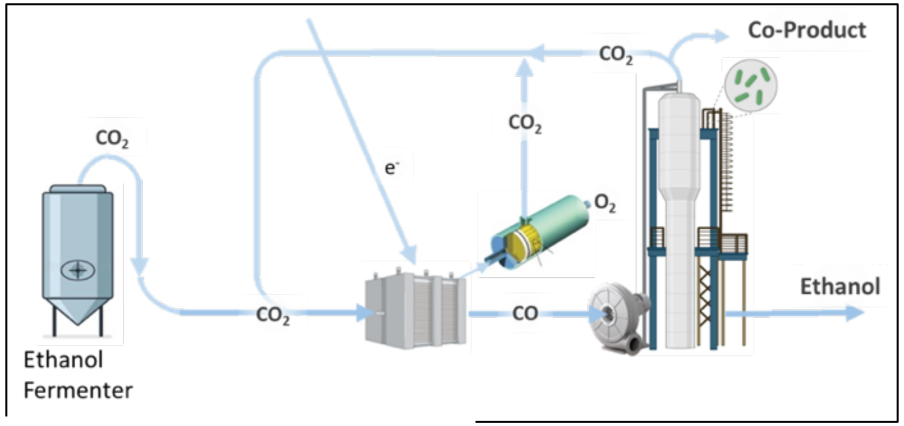
What If We Could Convert Biogenic CO_2 From a Gen. 1 Ethanol Refinery into Additional Product?

- 90 MM Gal/yr. biorefinery produces 27 T CO_2/hr.

- converted this CO_2 could increase production by ~40%

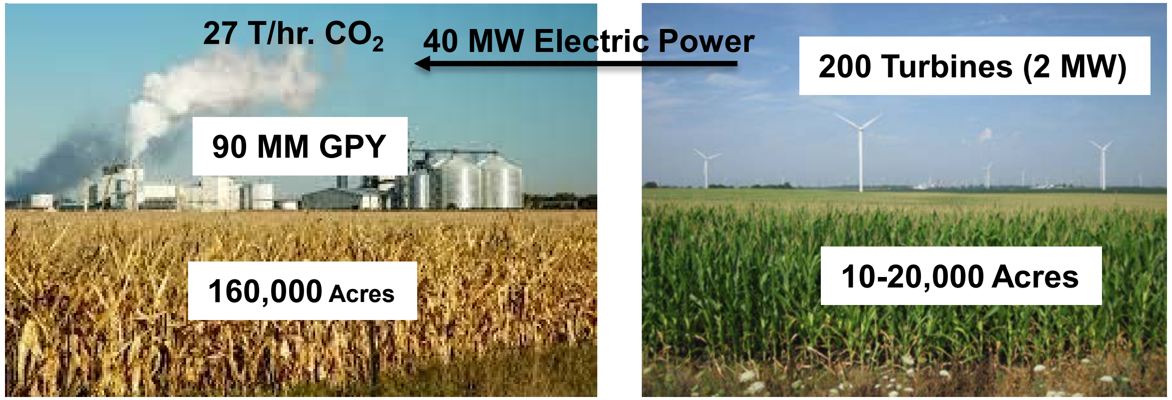
- 40 MW of power for CO_2 electrolysis
- 165 MW for H_2 production

  – 2 MW Wind Turbine
  – Capacity factor: 35%
  – Acres per turbine: 80
  – Turbines needed: 200



90 MM GPY Refinery Will Need 1600,000 Acres of Corn Field

200 Turbines (2 MW) Can Produce 40 MW at 30% Capacity Factor



There is enough space available in corn fields to install wind turbines to produce power to convert all of the biogenic CO_2 from fermentation

Internal Advisory Board (IAB)

LBNL – **Blake Simmons**, Division Director, Biological Systems & Engineering

NREL – **Adam Bratis**, Associate Lab Director

LLNL – **Roger Aines**, Energy Program Chief Scientist in E Program

ANL – **Seth Darling**, Chief S&T Officer, Advanced Energy Technologies Directorate

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Anteres Antoniuk-Pablant – Carbon Direct

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Mich Hein – Electrochaea

Thermochemistry/Fuels
Clare Behrens – Leidos
Aalo Gupta – Phillips 66

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LanzaTech

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CO2RUe

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Q&A

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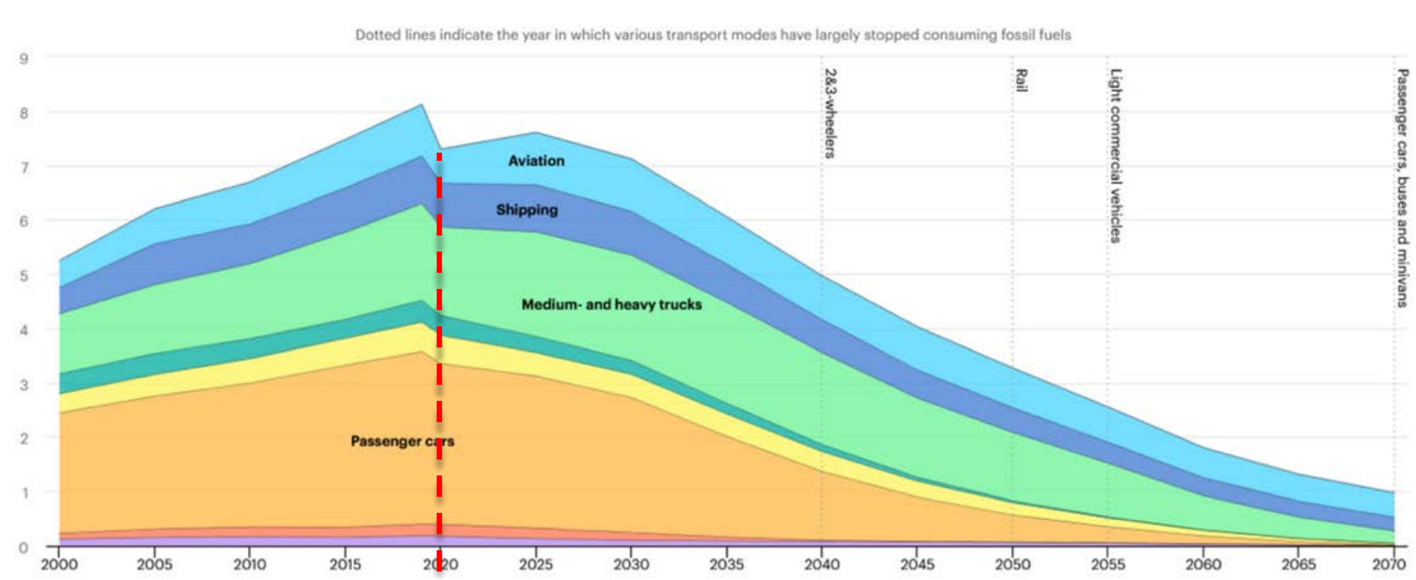
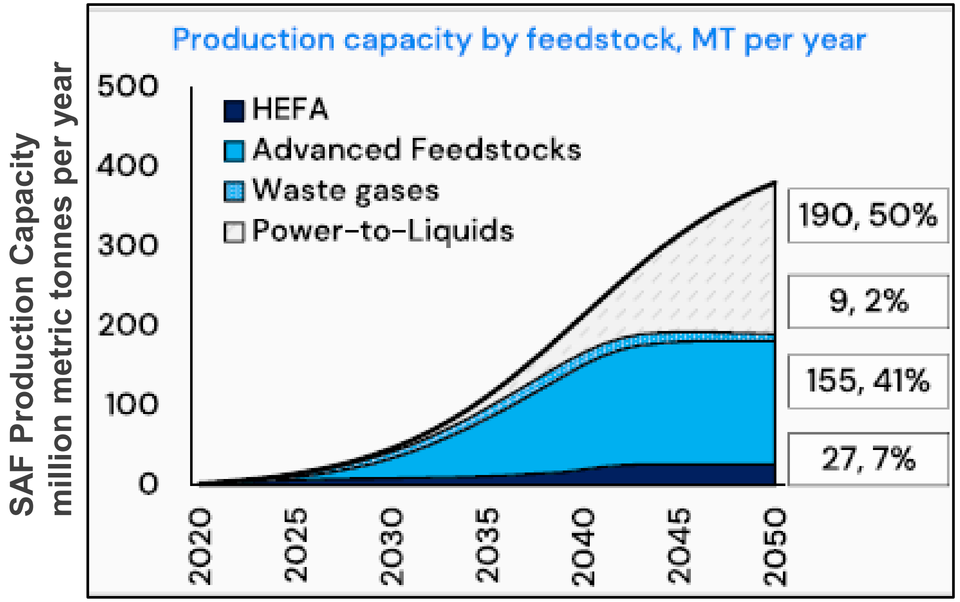
Project Overview: *A Change in Trends*

Electrification of the Transportation Sector



Increasing SAF Demand



Challenge: *Commercial shipping and transportation expected to be difficult to electrify/decarbonize. Projected supply of traditional biomass feedstocks may be insufficient to fully meet global demand.* CO_2 *as a feedstock could help meet SAF Grand Challenge*

IEA, energy technology perspectives 2020
ICF, Fueling Net Zero: How the aviation industry can deploy sufficient sustainable aviation fuel to meet climate demands