ARPA-E Efforts in Carbon Dioxide Utilization

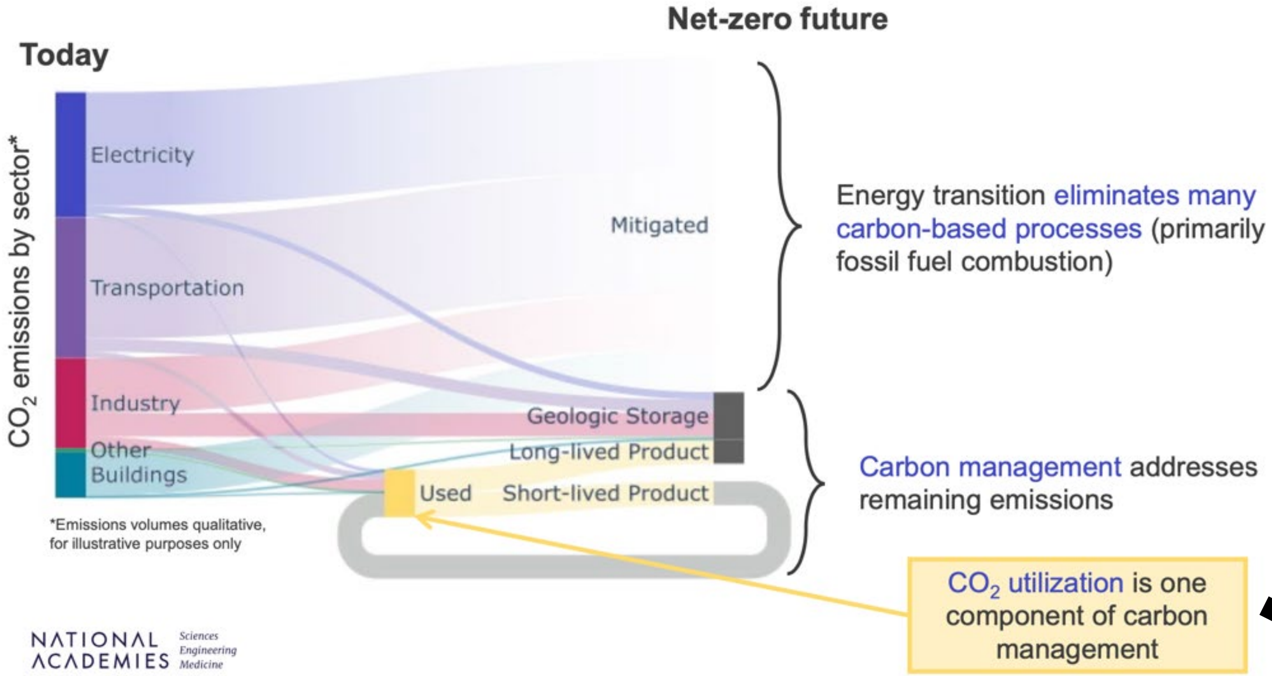
Briefing to National Academies Committee on Carbon Utilization Infrastructure, Markets, Research and Development

February 27, 2023

Agenda

- Introduction
- HESTIA Program- CO_2 Utilization for products – multi-routes to building materials
- ECOSynBio Program- CO_2 Utilization route – synthetic biology
- MINER Program - CO_2 Utilization route - mineralization
- New opportunities in distributed power --> liquids via reactor efficiency

Creating New Learning Curves in Carbon Utilization



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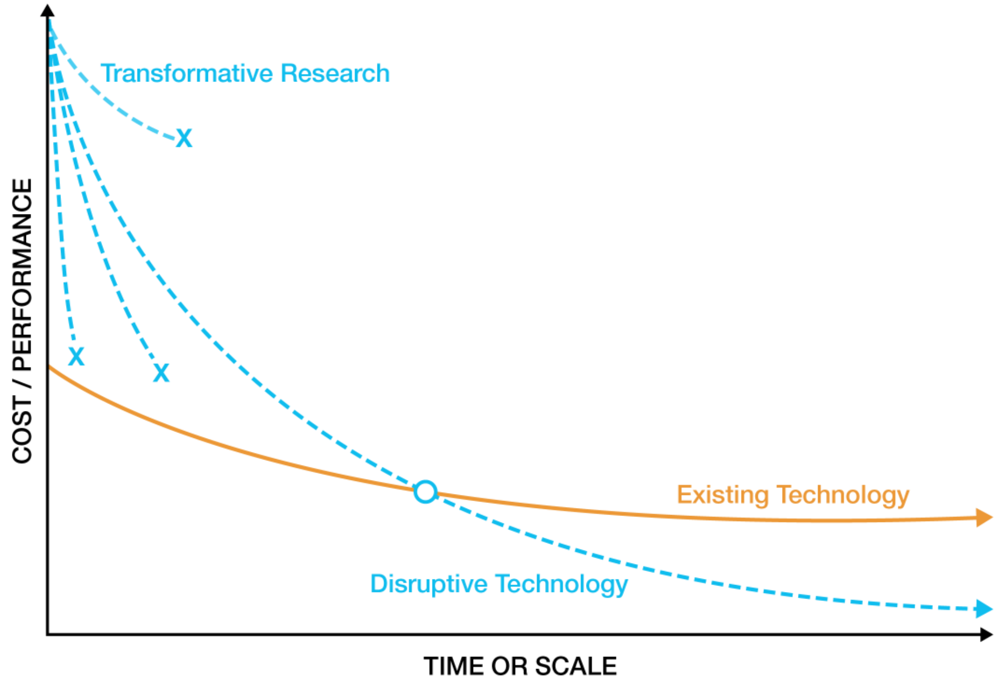

Source: *National Academies, Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities A First Report*

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CHANGING WHAT'S POSSIBLE

ARPA-E Program Portfolio

ELECTRICITY GENERATION & DELIVERY

Active

- CURIE (new)
- ONWARDS
- SHARKS
- BETHE
- GAMOW
- PERFORM
- GEMINA
- ATLANTIS
- DAYS
- MEITNER
- INTEGRATE
- IONICS
- GRID DATA
- NODES
- GENSETS

Alumni

- MOSAIC
- ALPHA
- CHARGES
- REBELS
- FOCUS
- SOLAR ADEPT
- HEATS
- GENI
- GRIDS
- IMPACCT

EFFICIENCY

Active

- MINER (new)
- HESTIA (new)
- REMEDY
- FLECCS
- REPAIR
- DIFFERENTIATE
- BREAKERS
- HITEMMP
- SENSOR
- CIRCUITS
- PNDIODES
- ENLITENED
- ROOTS
- SHIELD

Alumni

- ARID
- MONITOR
- DELTA
- SWITCHES
- METALS
- REACT
- BEETIT
- ADEPT

TRANSPORTATION

Active

- EVS4ALL (new)
- ECOSYNBIO
- ULTIMATE
- ASCEND
- REEACH
- SMARTFARM
- MARINER
- REFUEL
- NEXTCAR
- RANGE

Alumni

- TERRA
- REMOTE
- TRANSNET
- AMPED
- MOVE
- PETRO
- ELECTROFUELS
- BEEST

+ OPEN 2009, 2012, 2015, 2018, & 2021 Solicitations
+ Seedlings, Competitions, Complementary Exploratory Topics
+ SCALEUP 2019 & 2021

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MULTIPLE PATHWAYS FOR CO_2 → BUILDING PRODUCTS

Harnessing Emissions into Structures Taking Inputs from the Atmosphere (HESTIA)

Marina Sofos, Program Director
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HESTIA

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CHANGING WHAT'S POSSIBLE

ARPA-E's HESTIA program expands NAS definition for building products

What is Carbon Dioxide (CO_2) Utilization?

- Chemical transformation of CO_2 from the atmosphere, water, or waste gas streams into a marketable product

- In this report, CO_2 utilization does **not** include:
  - uses of CO_2 that do not involve a chemical transformation (e.g., enhanced oil recovery, fire suppression, beverage carbonation)
  - chemical transformations of CO_2 resulting in non-traded products and goods (e.g., soil carbon, ocean mineralization)

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Icons from Flaticon.com 4

HESTIA

NAS Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities A First Report

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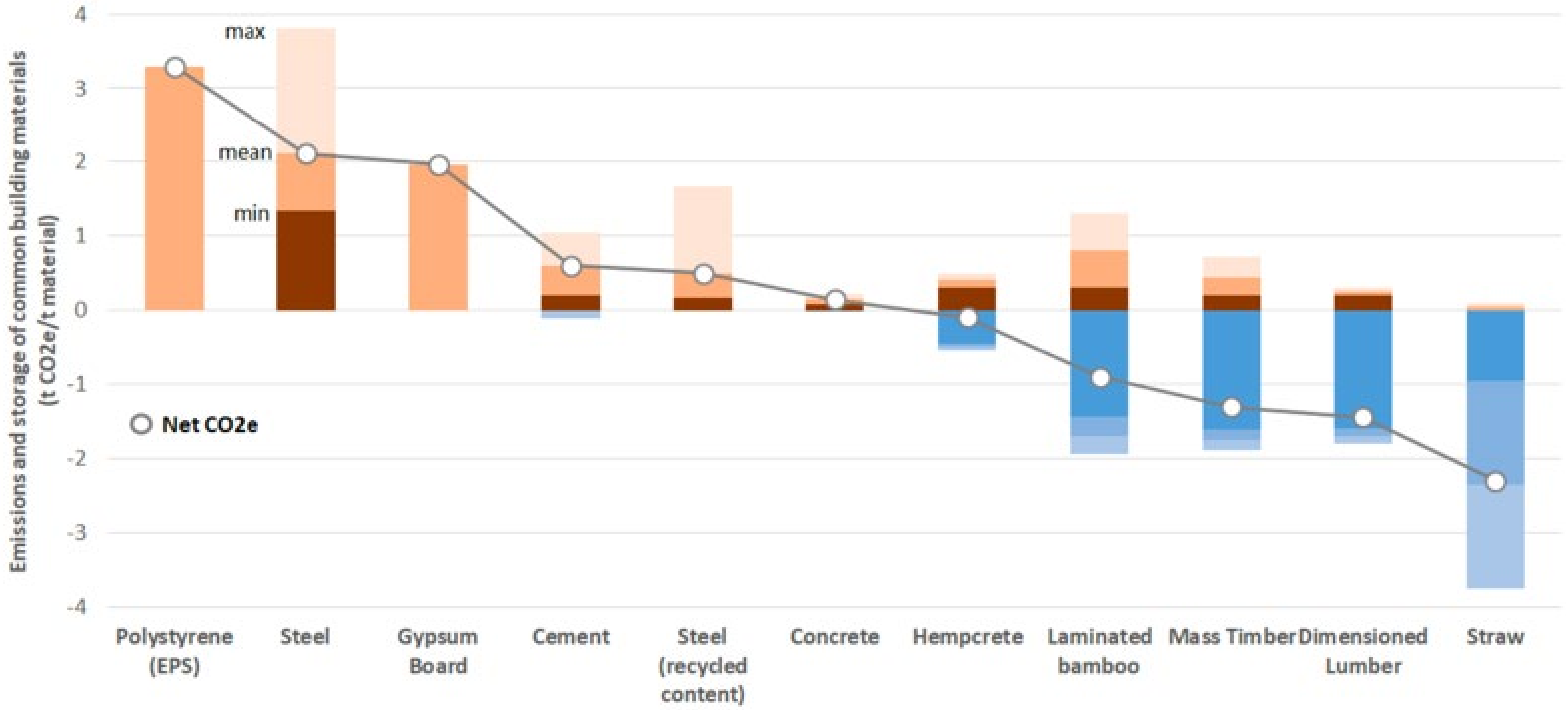
HESTIA seeks to address today's barriers to CO_2-derived building products

- Promising materials are emerging in use, but have limited code-compliant options
- Scarce, expensive, and geographically limited



Data from:

Pomponi,F.andMoncaster,A.”ScrutinisingEmbodedCarboninBuildings:TheNextPerformanceGapMade Mainfest, ”Renewable and Sustainable Energy Reviews, V. 81(P2), 2431-2442, 2018, DOI: 10.1016/j.rser.2017.06.049.

Ruuska.,”CarbonFootprintforbuildingproducts,”2013,https://cris.vtt.fi/en/publications/carbon-footprint-for- building-products-eco2-data-for-materials-an.

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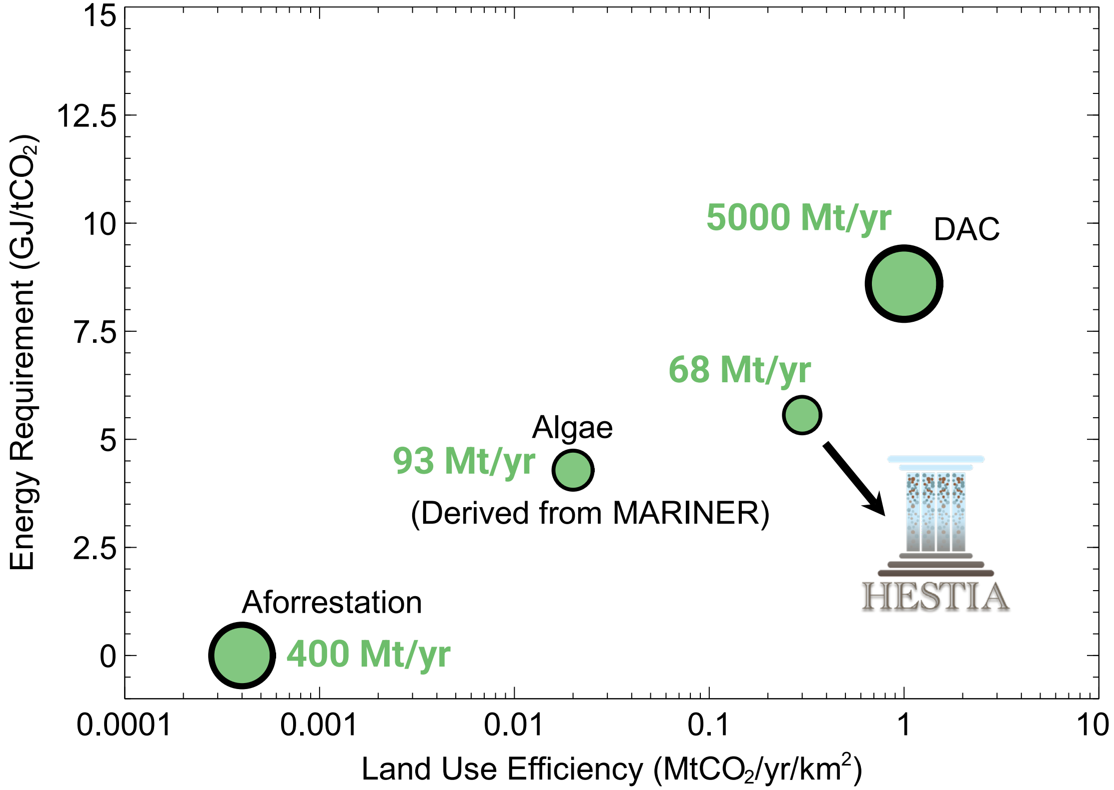
HESTIA

Harnessing Emissions into Structures Taking Inputs from the Atmosphere

Goals

Develop & demonstrate **building materials** & **whole-building designs** from a wide range of feedstocks (e.g., forestry & purpose-grown products, agricultural residues, direct carbon utilization) that are **net carbon negative** on a life-cycle basis by using atmospheric CO_2* in the production process.

Program Director	Dr. Marina Sofos
Year	2022
Projects	19
Funding Amount	$45 million
Status	Active



Data from:
Srubar III, W.V. "Can We Grow Carbon-Storing Buildings?" in *Build Beyond Zero: New Ideas for Carbon-Smart Architecture.* B. King & C. Magwood, Eds. In press;
BNEF; MARINER program; carbonplan.org

*Greenhouse gases (GHGs), measured in CO_2 equivalents, originally absorbed from the atmosphere through means including biomass growth and/or direct capture (from air or the ocean)

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HESTIA Program Structure

FOA Category A: Building Materials	FOA Category B: Building Designs with at least one c-negative material
Material Prototype	Architectural Plans + Material Prototype

Metrics:

GHG Impacts on LCA bases:

- Cradle-to-gate carbon negative with no increase to gate-to-grave @ **material level**
- Cradle-to-grave carbon negative @ **whole-building level**

Prototype Performance:

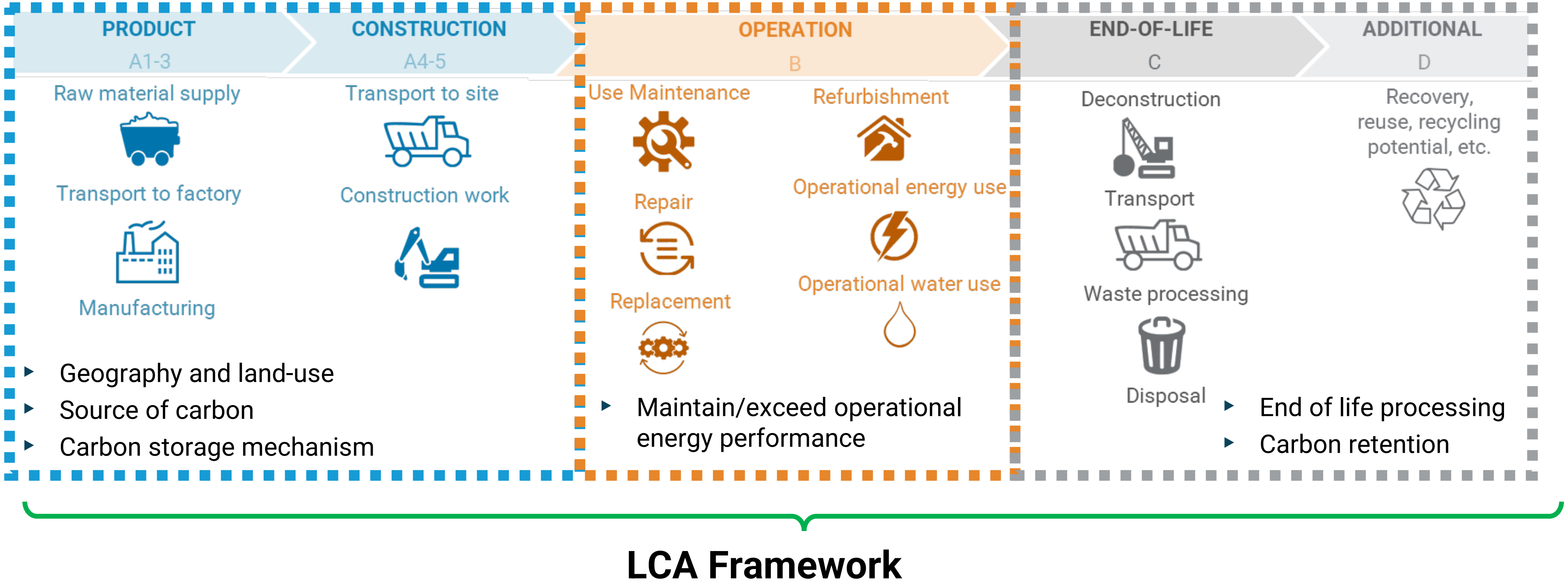
- Relevant **performance testing** (e.g., flammability, strength) per applicable building code & incumbent specifications
- **Market advantage** (e.g., improved performance in at least one building construction or operational energy usage requirement, lower cost, or easier installation) over best-in-class incumbent building element (i.e. structural and/or enclosure) selected for replacement
- Demonstration of recycling, repurposing and/or reusability potential to enable **longer service life** and/or **minimize end-of-life emissions**

Exploratory Topic
Life-cycle Analyses (LCA)

LCA Teams to Consistently & Accurately Evaluate Environmental Impacts

- Cradle-to-Gate/Grave
- Comparative Analysis (multiple indicators)
- Sensitivity Analyses
- Annual LCA stage-gates for continuous improvement

Program optimizes CO_2-derived building products



- **Carbon negative material:** Embodied emissions < atmospheric GHGs captured & stored (in any form) in the material itself over a specific time period

- **Carbon negative building**: Total embodied + operational emissions (including routine maintenance & replacement of common building elements) < atmospheric carbon stored in the materials of the building itself (only theoretically possible today)

Both timescales are being pursued in HESTIA

Long-term: centuries time scale, including “permanent” storage options

- Mineral materials

Medium-term: “temporary” storage on the order of years to decades.

- Biogenic materials

Sources: *Blue Plant Systems Corp.; CalPlant*

Expansion of bio-based feedstocks intended to:
(1) lengthen time horizon for increasing CDR capacity; and
(2) increase C storage time scale for bio-based waste, residues

**Short term storage, i.e. immediate use applications such as fuels, is out-of-scope for HESTIA*

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Innovations in LCA for assessing carbon utilization

- Sharpening pencil when modeling regional differences in biogenic materials production (e.g. land use change, regional cultivation practices, etc.)
  - Spatially-explicit LCA models

- Tracking emissions/uptake over time
  - Dynamic LCA (including carbon stored/released over time)

- Life cycle data for novel materials that do not exist in literature/databases
  - Consider uncertainty
  - Develop new ways to predict LCI based on material properties

?

CLF Carbon Leadership Forum W UC DAVIS

Final deliverable: open-source LCA tool for use by the Architecture, Engineering, & Construction community

Diverse portfolio of feedstocks, routes, materials & finished products

Insulation Materials

NREL — National Renewable Energy Laboratory
Beetle-killed wood → cellulose-mycelium

Aspen Products Group, Inc.
Recycled materials & ag residues → cellulose

UB
Cellulose/straw/hemp/wheat waste & silica aerogels → interlocking superinsulation panel

The University of Tennessee Knoxville
Waste lignin → non-isocyanate based polyurethane foam

New "Wood" Materials

Bamcore
Bamboo slats & chips → superinsulation panel

Purdue University
Fungi & bacteria → "living" wood structure

Oregon State University
Small diameter waste wood → wood wool cement composite

Composite Materials

SkyNano Technologies
C-fiber waste, C-nanotubes & bamboo → composite

Cementitious Materials

Wisconsin — University of Wisconsin–Madison
Upcycle industrial mineral waste via DAC → geopolymer cement

NREL — National Renewable Energy Laboratory
SAF production process waste → bio-ash SCM w/ biochar

BioMason
Biogenic urea → bio-based cement

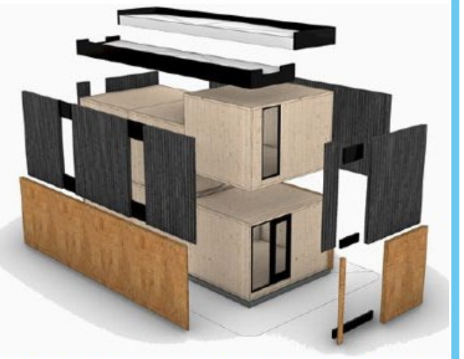
CU
Biogenic limestone ($CaCO_3$) from calcifying microalgae → bio-based portland cement

Maximizing carbon utilization potential via new building designs

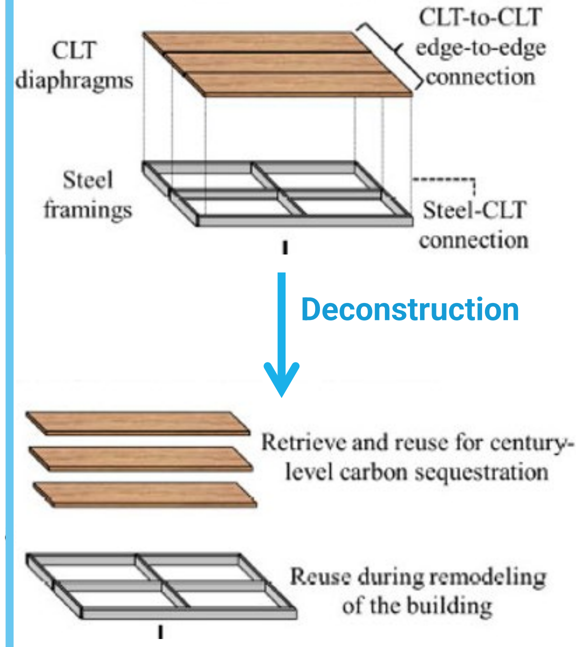
- Link design decisions w/ material selection → maximize carbon storage
- Design for disassembly and reuse → increase service life/carbon retention

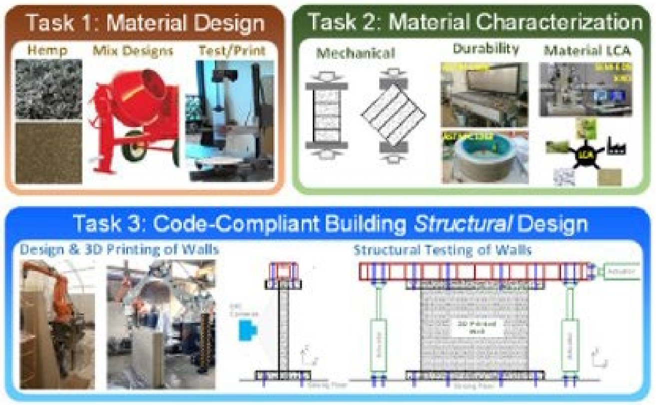
Building Design Teams

Pacific Northwest
NATIONAL LABORATORY

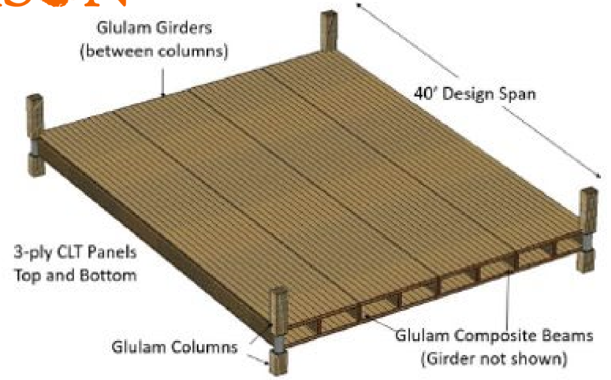


Northeastern





CLEMSON



Penn
UNIVERSITY of PENNSYLVANIA

ECOSYNBIO

Kirk Liu, Technology-to-Market Adviser
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ECOSynBio

Energy and Carbon Optimized Synthesis for the Bioeconomy

Mission

Develop new technologies/tools that significantly improve bioconversion carbon efficiency, leveraging the use of external reducing equivalents

All systems will demonstrate the capacity to accommodate external reducing equivalents

Novel biomass systems will utilize external energy inputs to substantially increase carbon utilization and target economies of scale for industrial applications

Program Director	Dr. David Babson
Year	2020
Projects	16
Funding Amount	$35 million
Status	Active

Goal Alignment with NAS Findings

- CO_2 Purification Requirements (from Findings 4.2 & 4.3)
  - Biological conversions utilizing high purity
- Strategic Co-Location (from Finding 6.4)
  - Program technologies considered for co-location with existing bioeconomy

Technical Categories

- Gas Fermentation
- Cell-free biocatalysis conversion platforms
- Non-oxidative glycolysis
- Consortia fermentation

ARPAE biological CO2 utilization program aligned to NAS definition

What is Carbon Dioxide (CO_2) Utilization?

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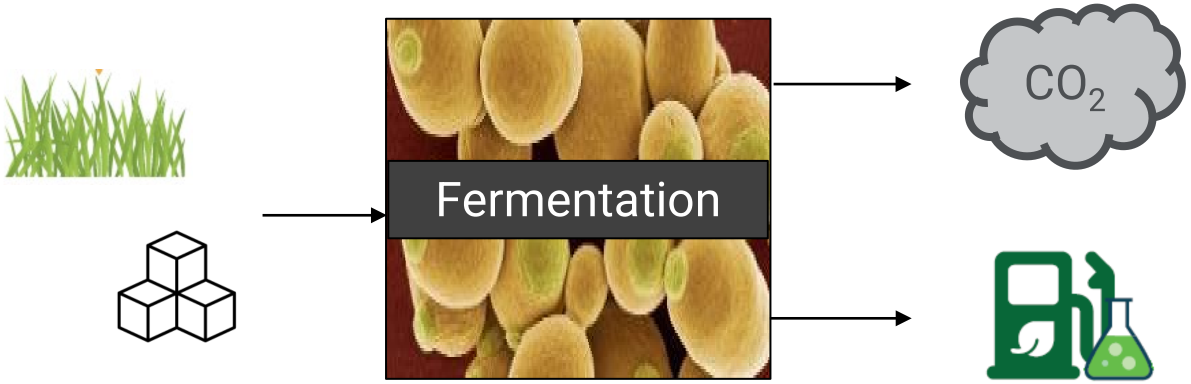
NAS Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities A First Report

Bioconversion not considered for carbon efficiency – liquid energy product

Fermentation

Sugar → Product + Carbon Dioxide

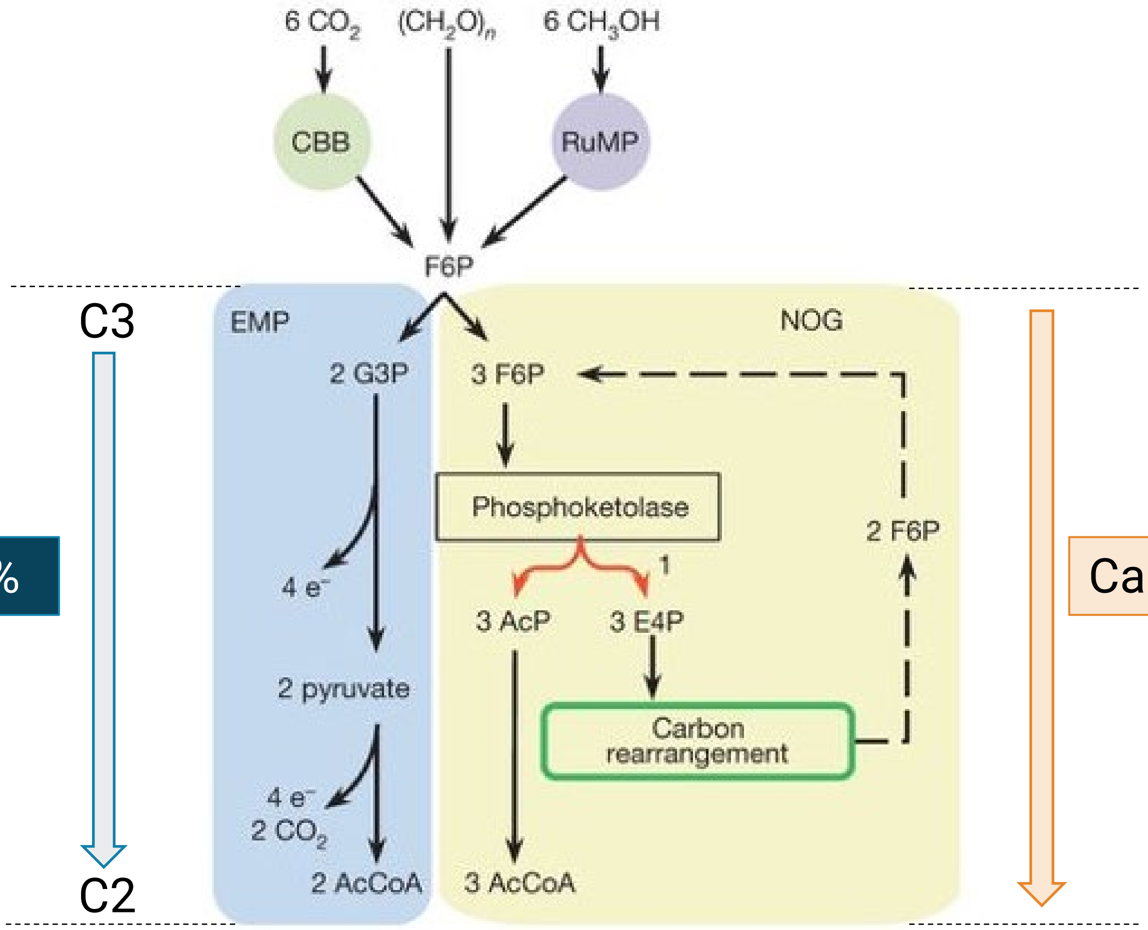
$$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$$



With assembly and added energy, engineered 100% carbon yield fermentation

Traditional Glycolysis | **Non-Oxidative Glycolysis (NOG)**

Carbon Yield = 66%



Carbon Yield = 100%

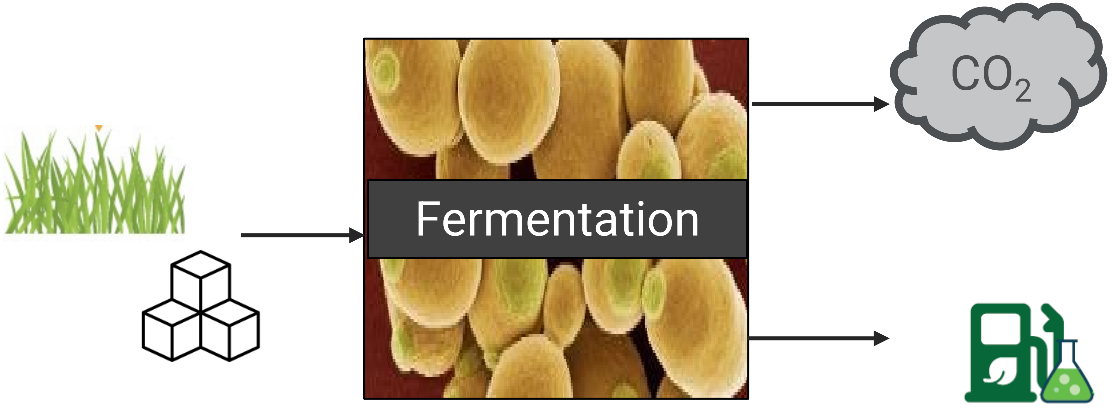
Bogorad, et. al. Nature, October 2013

Design system accommodate reducing equivalent to drive carbon efficiency

Fermentation

Sugar → Product + Carbon Dioxide

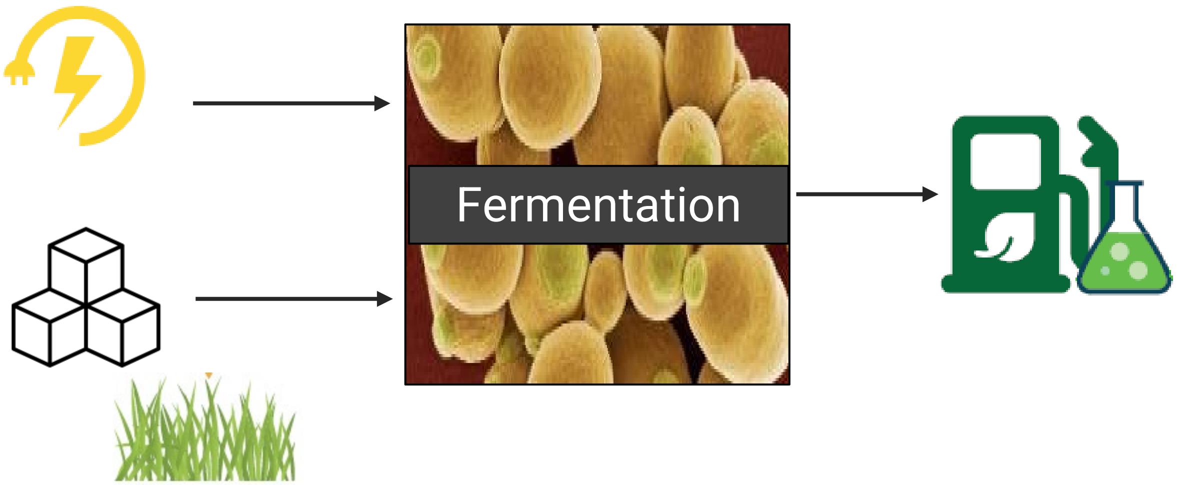
$$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$$



Carbon Efficient Fermentation

Sugar + Reducing Equivalent → Product

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

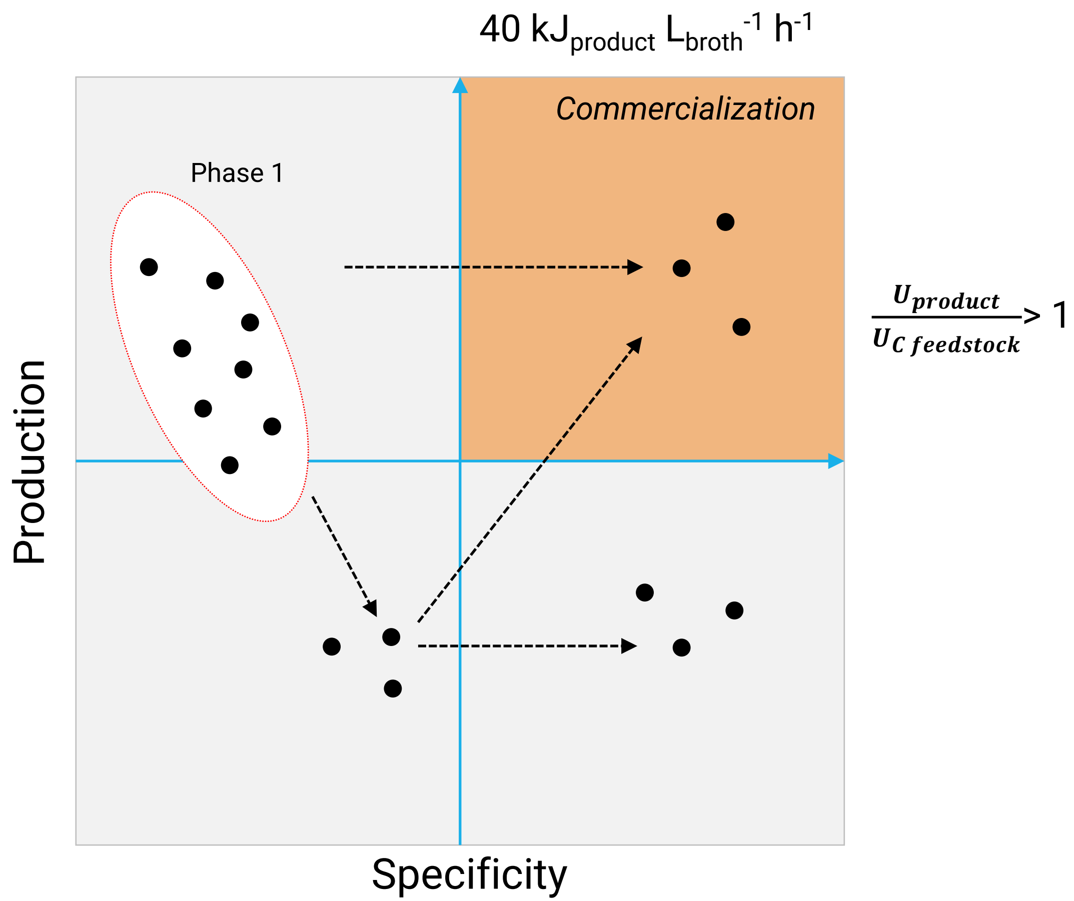


Program challenge to tackle established commodity markets

Program Metric Considerations

Key output yield Specific energy ratio	$\frac{U_{product}}{U_{C\ feedstock}} > 1$
Avoided CO_2 evolution (system basis)	100%
Production rate	40 $kJ_{product}\ L_{broth}^{-1}\ h^{-1}$
External reducing equivalent accommodation	Biological energy carriers regenerated electrochemically and/or from H_2O / CO_2

Program Commercialization Illustration



Diverse portfolio of technical approaches – program themes

Gas Fermentation	WISCONSIN UNIVERSITY OF WISCONSIN–MADISON; LanzaTech; Circe
Mixotrophic Consortia / Synthetic Ecology	University of Delaware; Berkeley University of California; Ohio State; MIT
Engineering Carbon-Efficient Pathways *Non-Oxidative Glycolysis*	NREL National Renewable Energy Laboratory; geno; Oregon State University; De Nora; Zymochem
Cell-Free Biosynthesis Biocatalysis	Stanford; UC Irvine; invizyne; University of Minnesota; University of Washington

MINER

Mining Innovations for Negative Emissions Resource Recovery

Dr. Douglas Wicks, Program Director
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MINER

Mining Innovations for Negative Emissions Resource Recovery

™

Mission

Develop commercially scalable technologies that would enable greater domestic supplies of copper, nickel, lithium, cobalt, rare earth elements, and other critical elements.

Program Director	Dr. Douglas Wicks
Year	2022
Funding Amount	$44 million
Status	Active

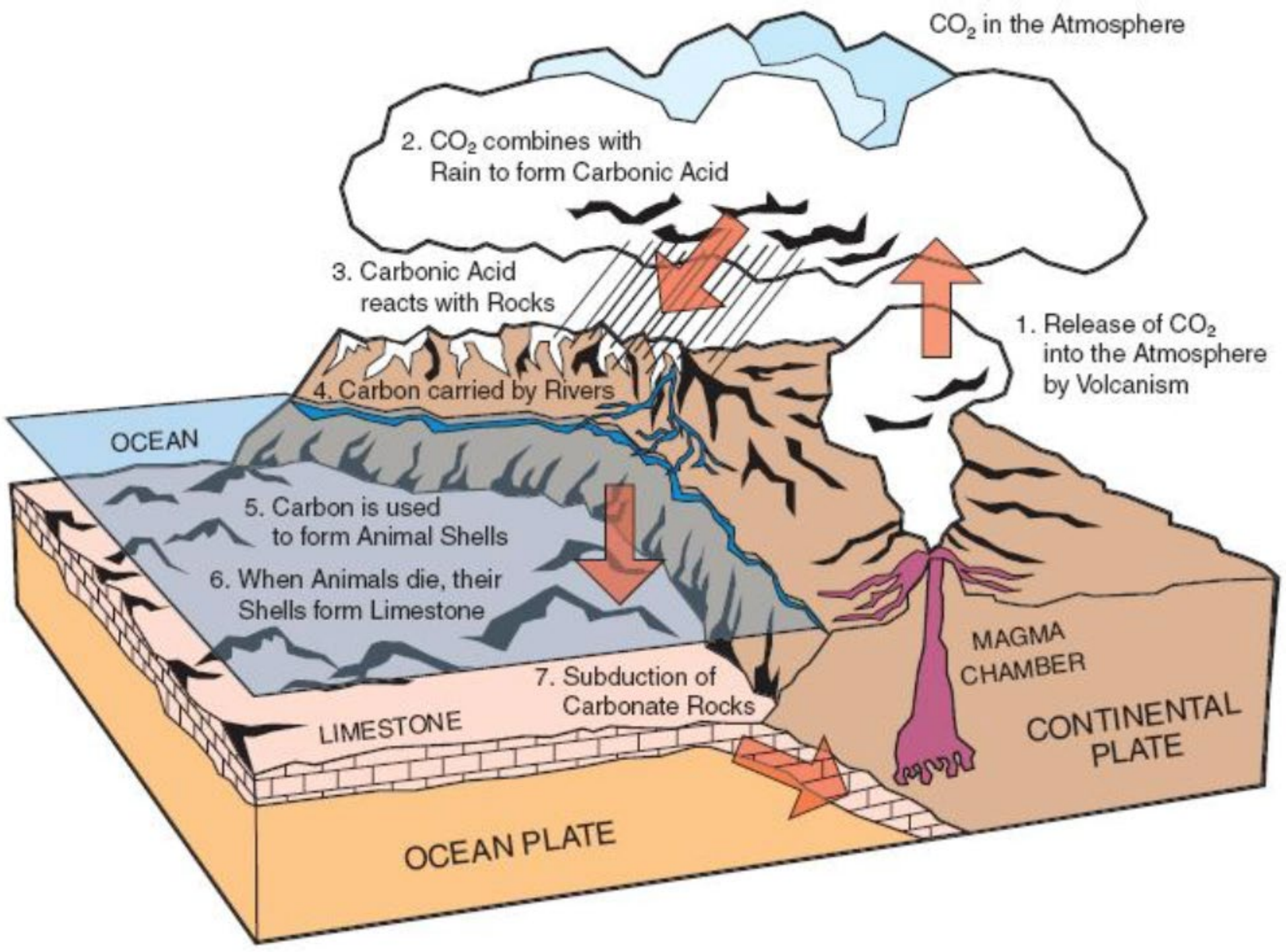
Goals

- Increase the mineral yield while decreasing the required energy, and subsequent emissions, to mine and extract these energy-relevant minerals.
- Investigate the potential CO_2-reactive ores to unlock net-zero or net-negative emission technologies.

Routes to Enable Mineral Extraction:

- Electrochemical
- Mineralization

Mineralization is a Natural Process that Sequesters CO_2



Nature's way takes WAY TOO MUCH time – literally ***eons***

- Basically reaction of ambient CO_2 and water with rocks
- Locks CO_2 away as stable carbonates

http://butane.chem.uiuc.edu/pshapley/Environmental/L29/2.html

How Improved Element Extraction Will be Accomplished

- Convert components of low-grade ores containing ER elements from harder to process forms to easier forms

Demonstrative reactions in olivine ore…

Mg_2SiO_4 + $2CO_2$ → $2MgCO_3$ + SiO_2 — CO_2 Mineralization

Ore has a lot of this

$NiSiO_3$ + CO_2 → NiX + [byproducts] — Energy-Relevant Element Form Change

Ore has a little of this

NiX = ferro nickel (35% Ni, 65% Fe), nickel oxides (NiO), pure nickel. NiO thermodynamically favorable over $NiCO_3$

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Mineralized products to be explored for multiple potentials

Increase Beneficiation Efficiency

Carbonates are easier to grind

Increase Metals

Gigatons of metals from CO_2-reactive minerals

Ex. olivine

(Mg, Fe, Ni)$_2$SiO$_4$ + CO_2

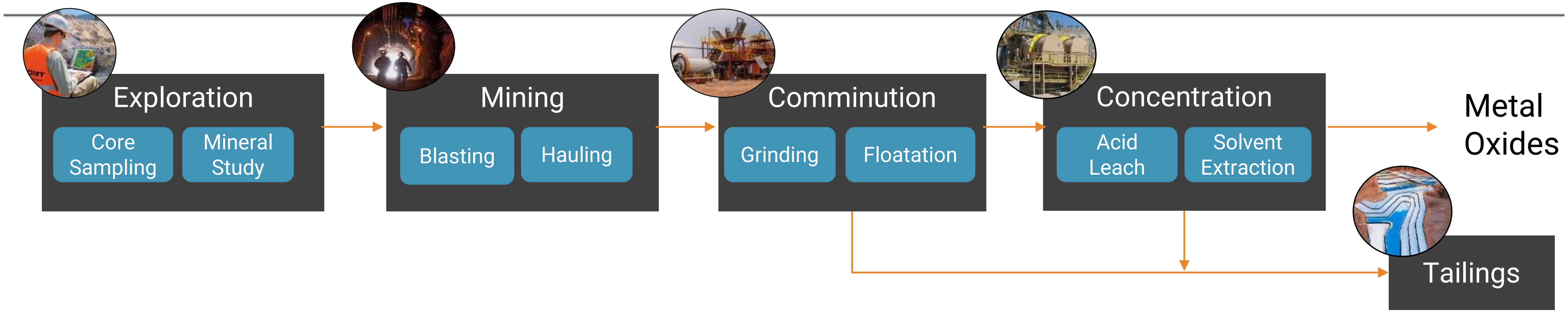
Carbon Sequestration

Gigatons of stable CO_2 storage potential

Modeling

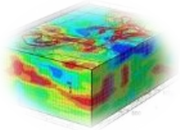
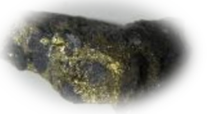
Carbonation, critical metal, and storage potential

Program impact across mineral value chain



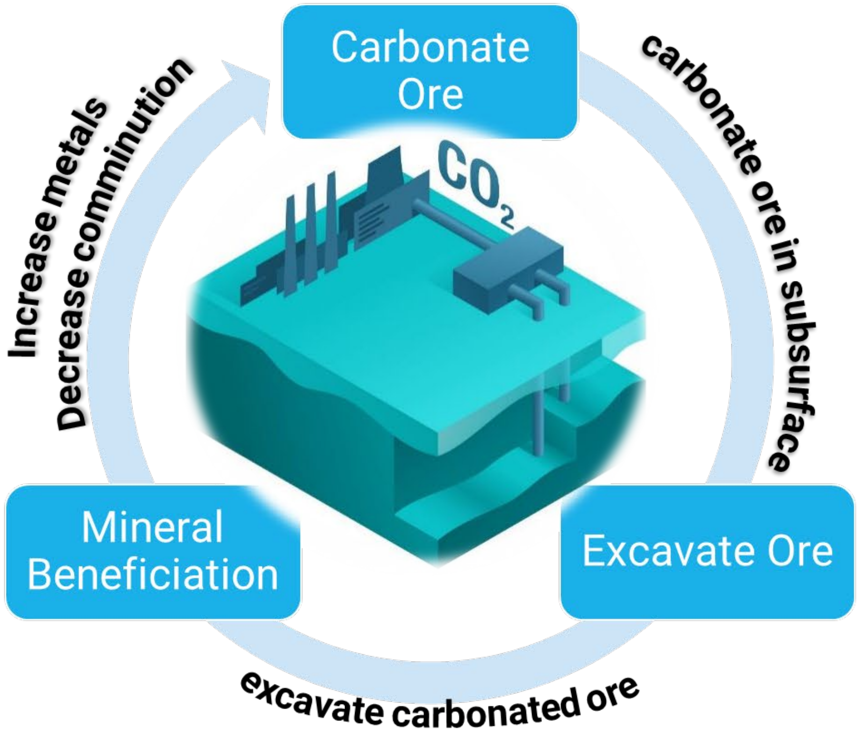
Teams	▪ Harvard ▪ CO Mines	▪ INL ▪ UT Austin ▪ PNNL	▪ Mich Tech ▪ UNev Reno ▪ Missouri S&T ▪ UKentucky	▪ VA Tech ▪ Columbia	▪ UT Arlington ▪ Columbia ▪ JHU ▪ Travertine ▪ PHX Tailing
Technology Example	Characterize carbonation potential	Research for novel in-situ fracturing, monitoring, and leaching techniques	Novel flowsheet design, mechanical equipment supercritical CO2, techniques to reduce overall energy use and GHG impact	Novel flowsheets for concentration of metals by carbonation	Utilize waste stream and recover residual minerals via CO_2 reactant

Program investigates multiple mineral deposits

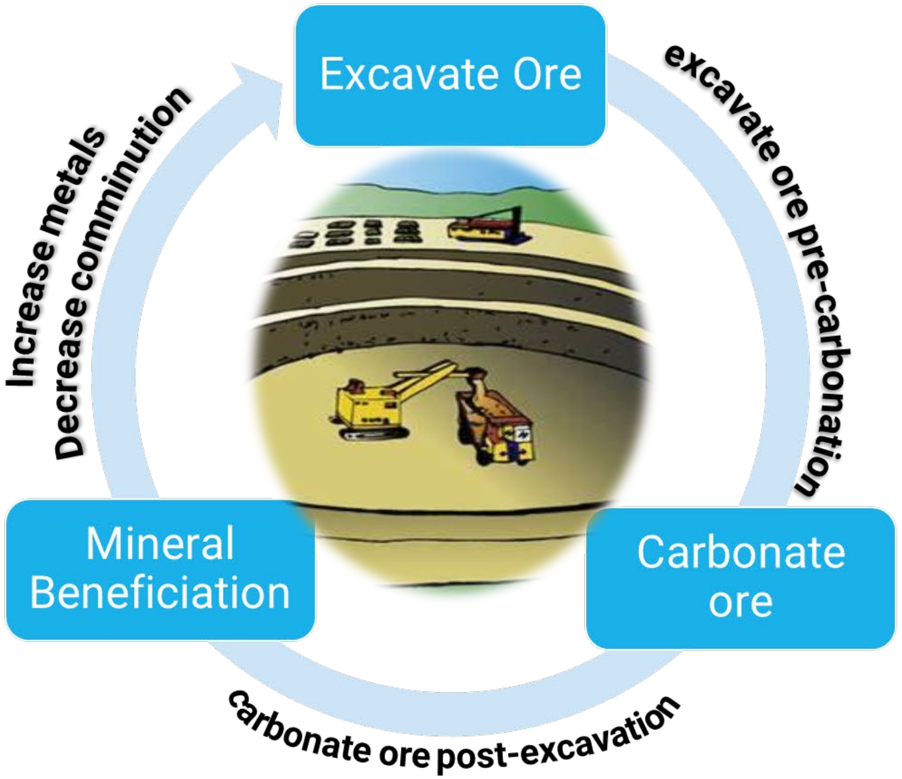
Metal Target		Team	Technology Scope
General Metal Deposits		**Harvard** *Schlumberger* **CO Mines** *Rio Tinto, VPI*	Subsurface carbonation characterization & monitoring
Ni-Co-PGE		**MST** *Sibanye-Stillwater, Talon, LANL* **INL** *Sibanye-Stillwater, Eden GeoPower, CSM* **Columbia** *Eagle Mine, Princeton, VPI*	In-situ carbonation, monitoring, fracking, metal leaching metal extraction, and electrochem acid leach
Ni-Co		**Travertine** *ANSTO, Monash, Alberta* **Phoenix Tailings** **MTU** *PolyMet Mining, Eagle Mine* **JHU** *Guelph, ANL* **UT Austin** *Canada Nickel, Carbfix, CNRS*	
Li-Ni		**UT Arlington** *Rio Tinto, UCLA*	Electrochemistry
Cu-REEs		**U. Kentucky** *Rio Tinto, MP Materials, Eriez Manufacturing, Solvay*	Milling, Flotation, Bioleaching
REEs		**U. Reno** *MP Materials, USGS*	Milling, Flotation
Cu-Ni		**Columbia** *Talon Metals*	Hydromet + Electrochemisry
Ni-Co-REEs		**VPI** *Western REE, Columbia, UVA, CSU*	Full Ore

Program technology themes

Example: ***In Situ***



Example: ***Ex Situ***



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Balanced and diverse carbonation research portfolio

7 Ore/Mineral deposit types/Metal targets
- Investigates carbonation and process for critical minerals Ni, Co, Cu, REE, PGE, Li

Spans exploration to beneficiation from ore to metal oxides
- Novel carbonation flowsheets or integration

Geographically diverse leads with industry partnerships
- 14 academic universities
- 2 national lab
- 2 small businesses

OPEN 2021: SAMPLE PROJECT

Jack Lewnard, Program Director
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Novel Tandem Design for Electrosynthesis of Pure Alcohols Using Diluted CO_2 Feed Stream

Mohammad Asadi, Illinois Institute of Technology (Chicago, IL)

Technology Summary

Develop a novel tandem electrocatalysis cell design for economically feasible and energy efficient conversion of CO_2 to valuable chemicals.

This unique design enables us to drive two sequential reactions in parallel with remarkable current density where the applied voltage is limited to that of the higher potential reaction.

Demonstrate a lab-scale electrolyzer (5cm^2) that works with a diluted CO_2 feed stream of higher pressure and temperature to effectively produce valuable chemicals.

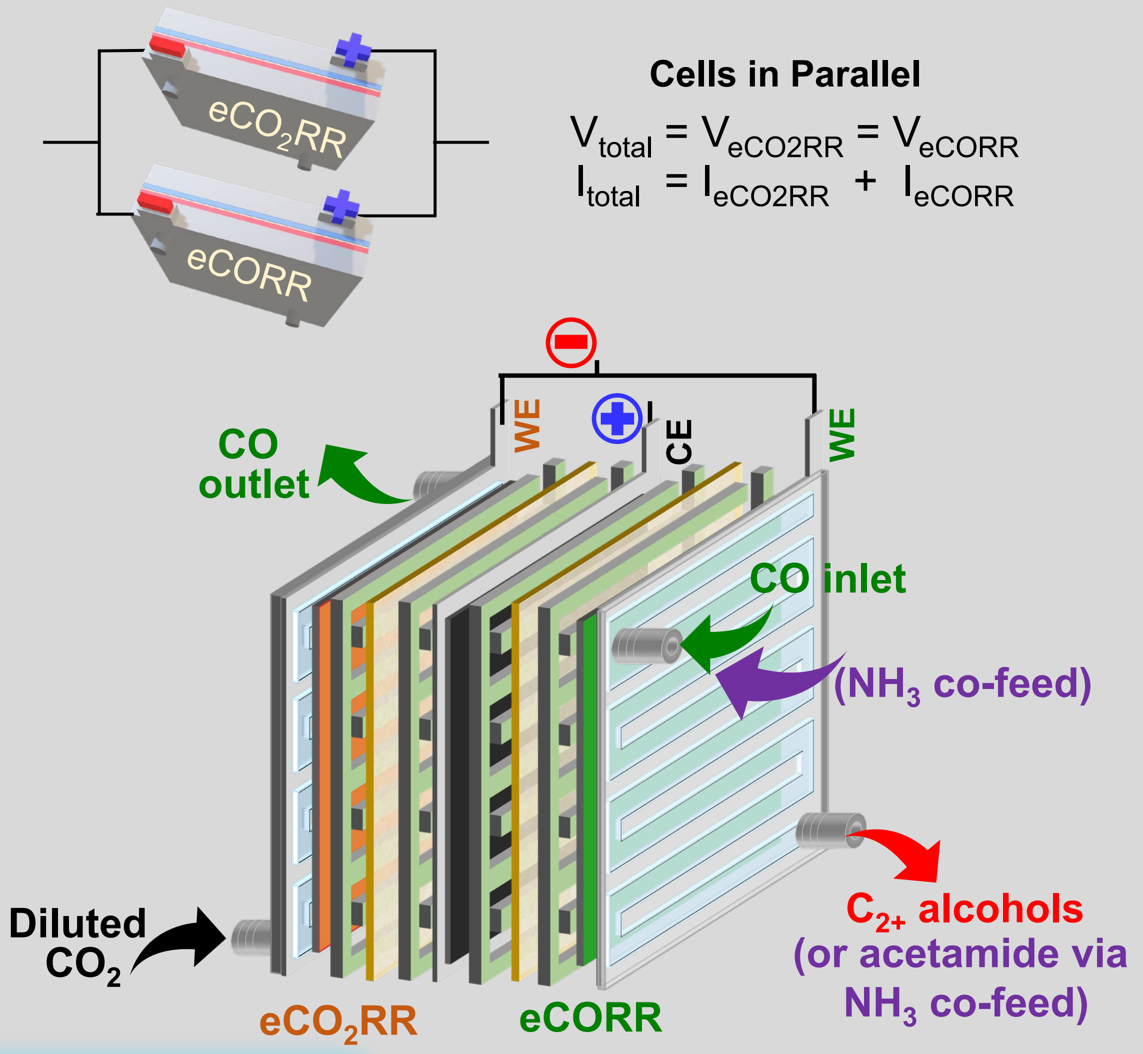
Technology Impact

40X higher reaction rate (current density) and 5X better selectivity of CO_2 electrocatalysis by significantly reducing required potential.

Sustainable production of a variety of chemicals with extremely high market values such as acetamide by co-feeding chemicals such as ammonia.

Production of propanol, and acetamide with an approximate retail sale price (RSP) of about \$730, and \$1471, respectively that are about 40% and 50% lower than current average market values.

Proposed Technology



CO_2 electrocatalysis to valuable products at 8X energy efficient, 40X higher reaction rate with 50% lower sale price.

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NEXT GEN. POWER TO LIQUIDS

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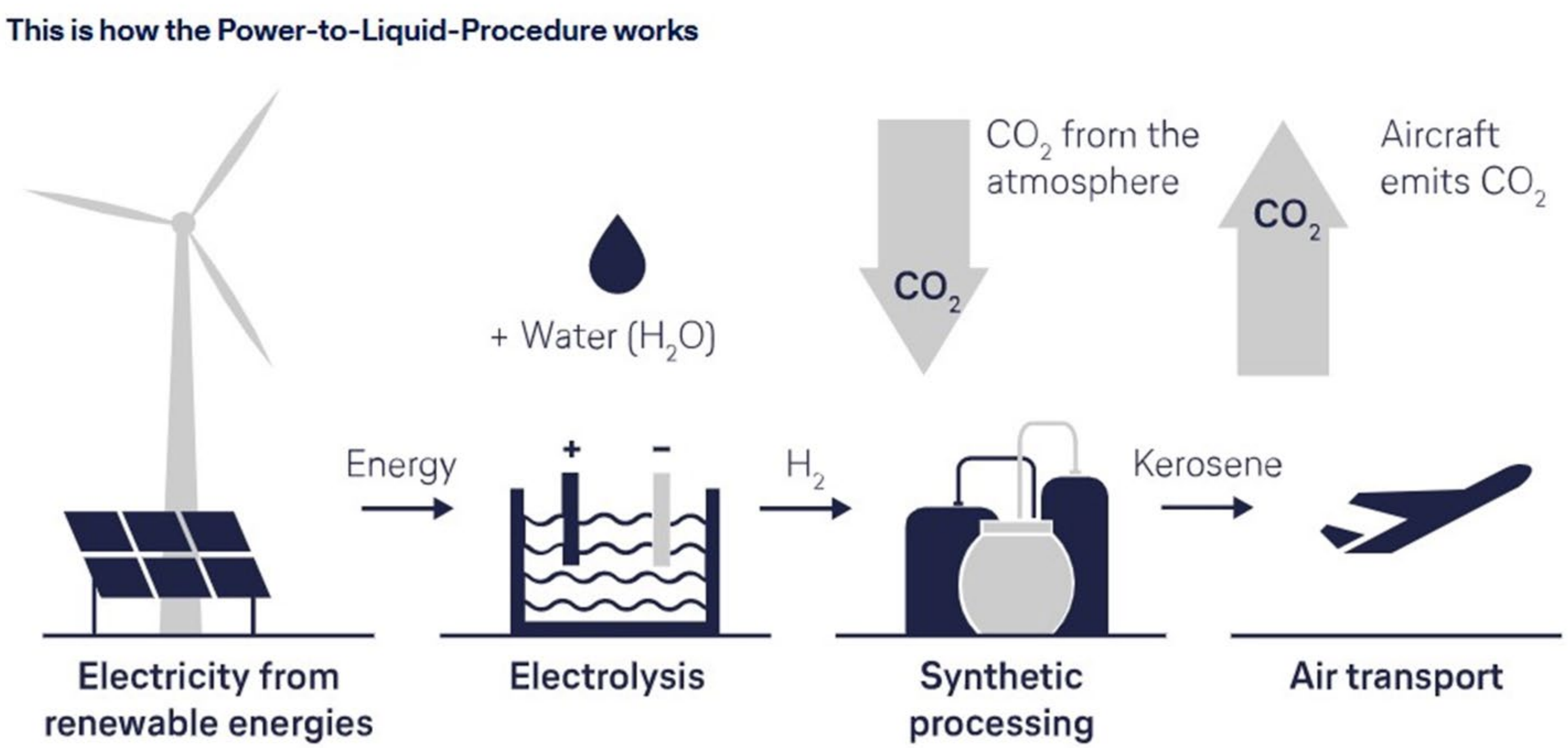
What is Power to Liquids



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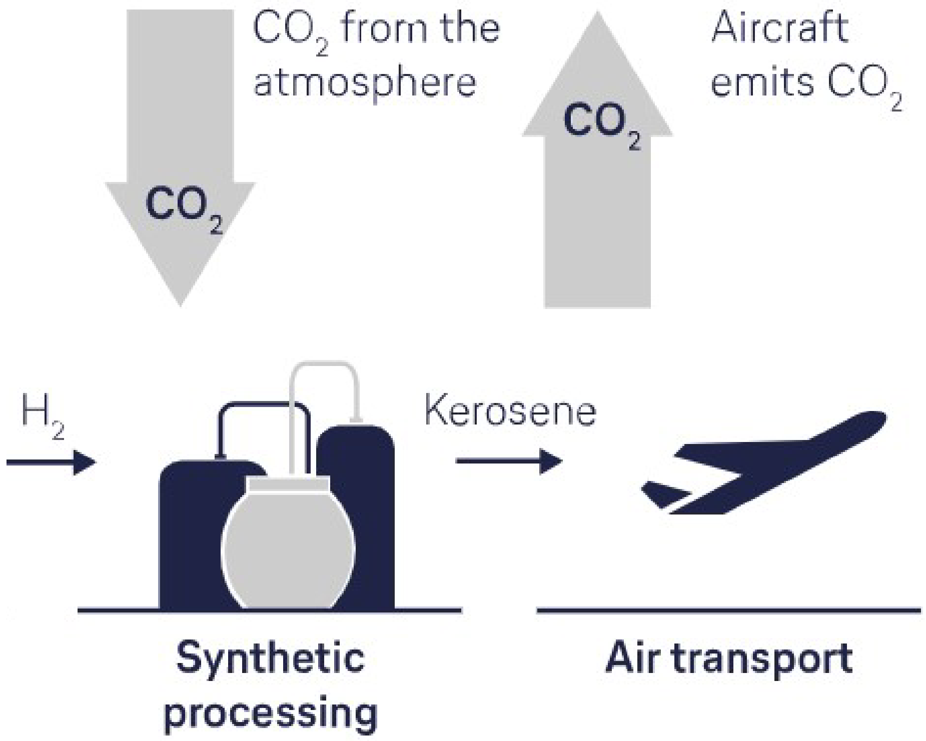
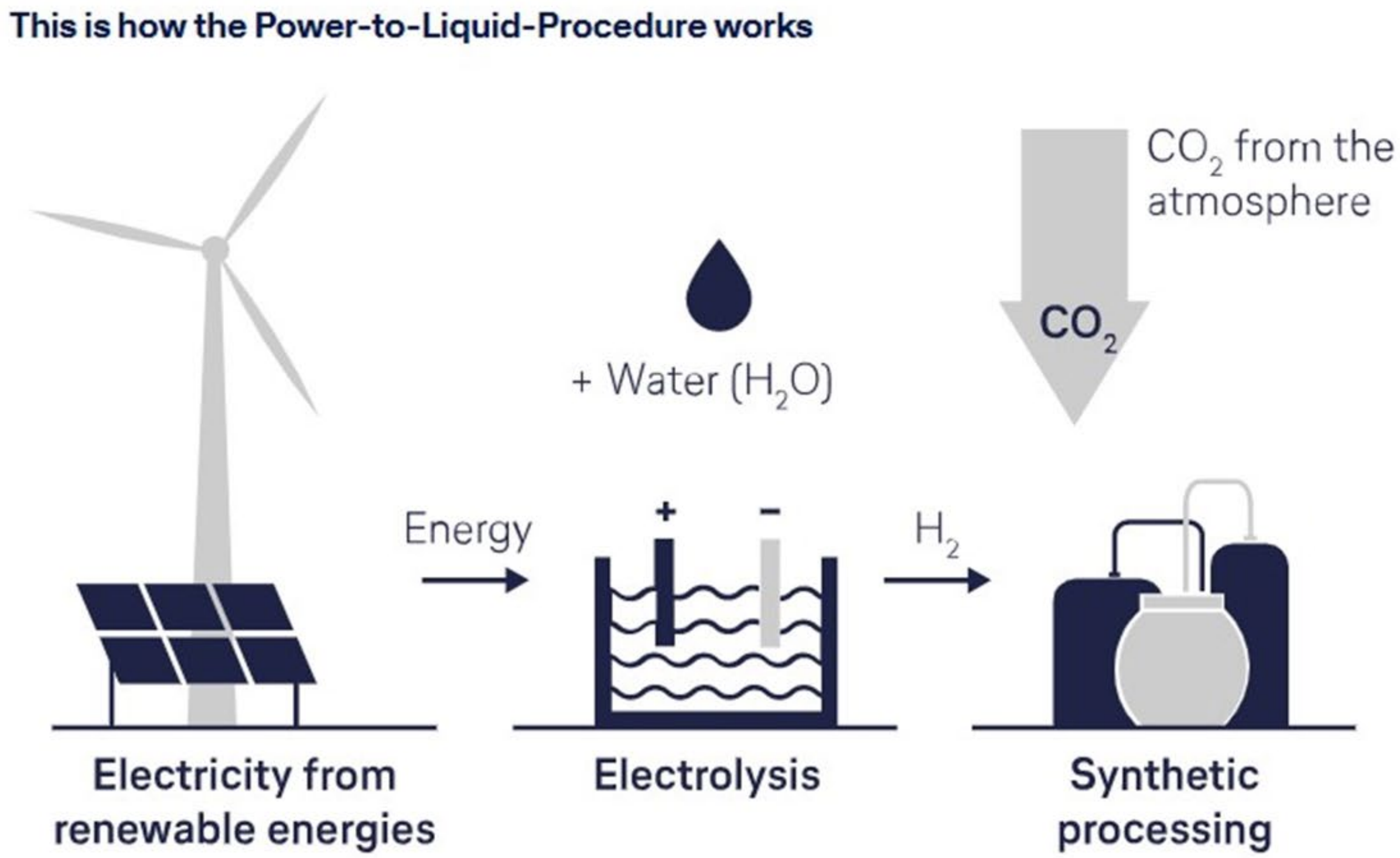
Reactor System is the key to unlock PtL

Focus on the reactor system

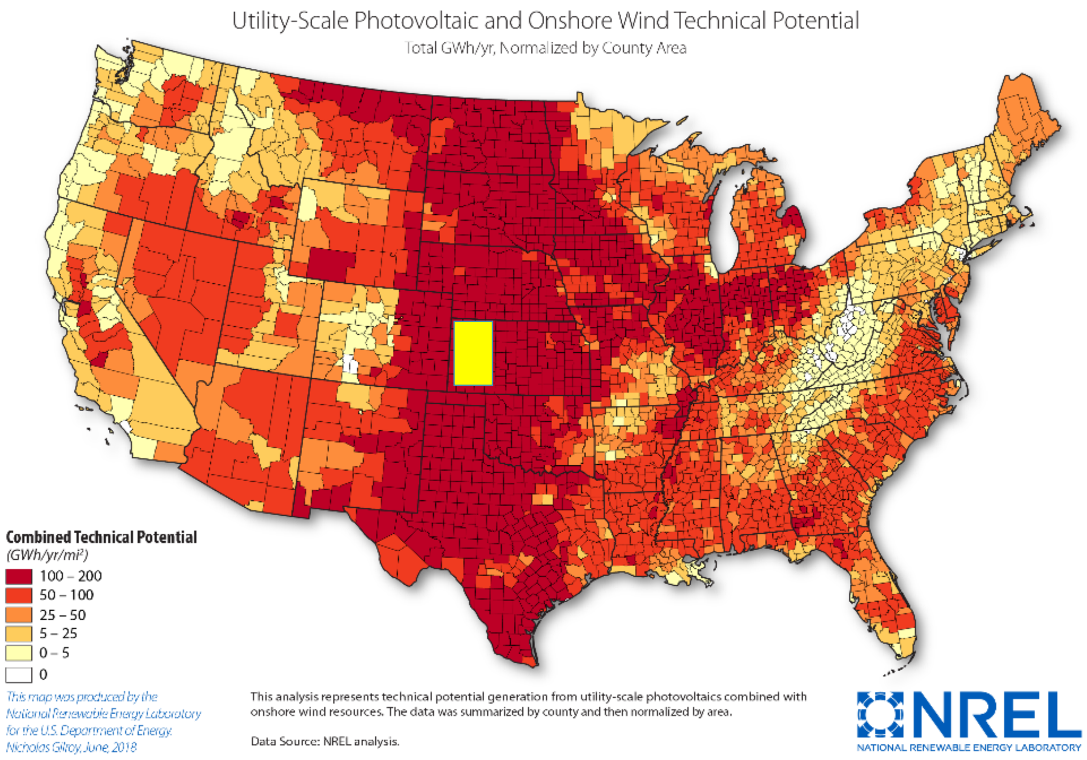


Integrate with Renewable Power at site



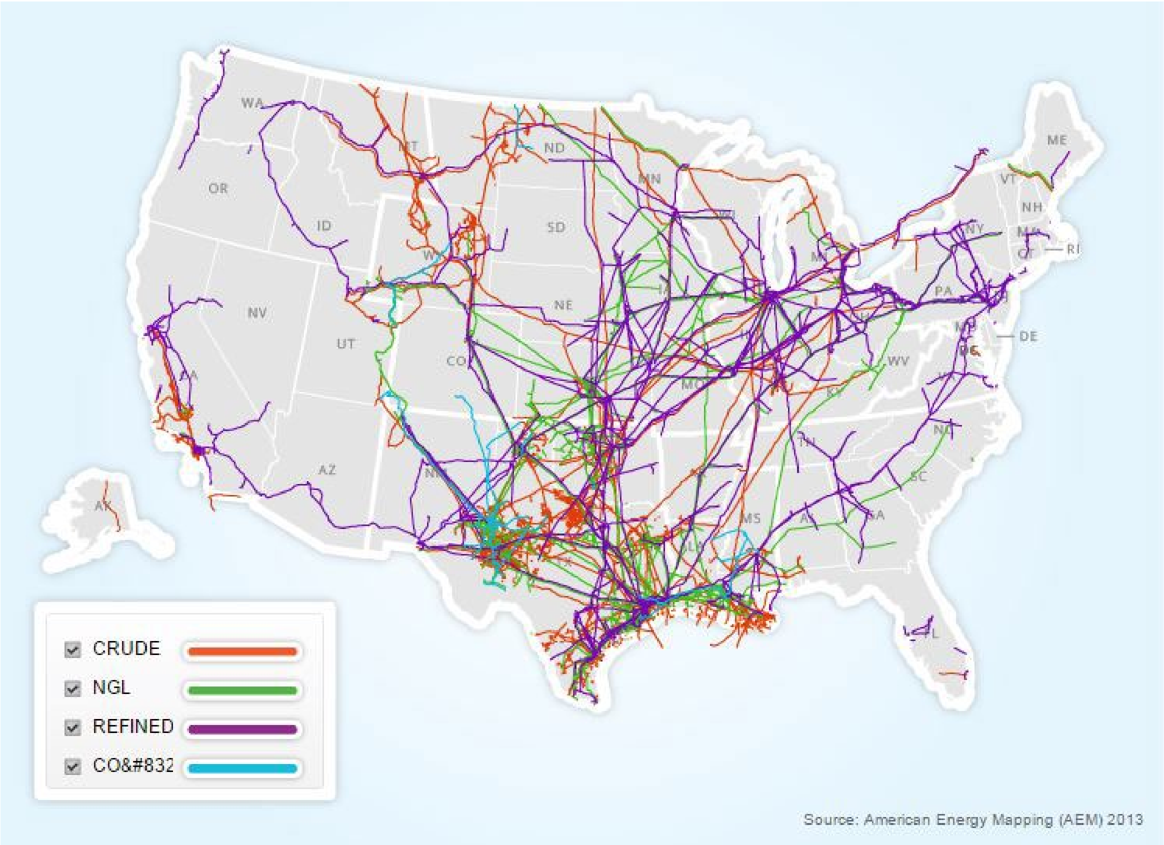
- Enabled by <$2/kg H_2
- 100 to 1000 BBL/D
- Target: $4/gallon

U.S. Renewable Resources and Infrastructure



6.5 MMBBL/D PtL Area

Wind and Solar Potential



Liquid Pipeline System

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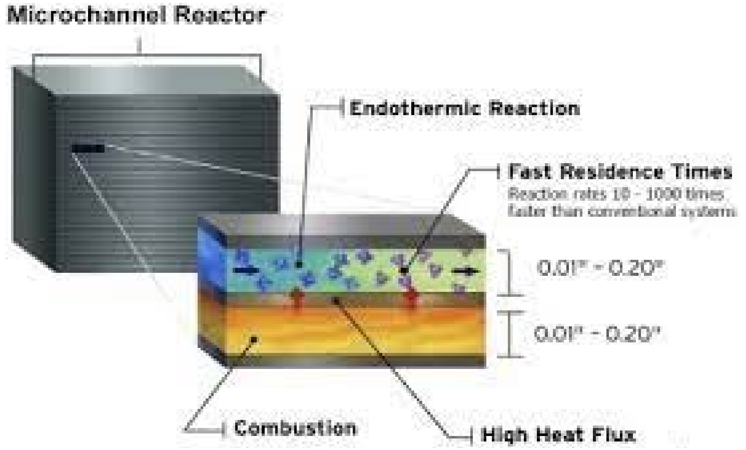
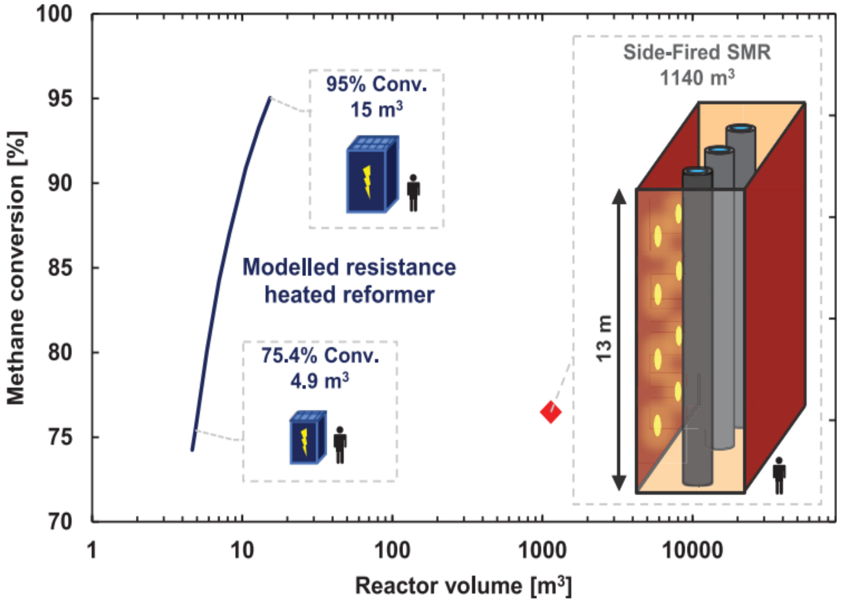
Next Generation Modular Reactor System?

- Modular Reactors
  - Microchannels
  - catalytic membrane
  - spinning disk
- Electrochemical reactors
  - CO2, HCO3 electrolysis
- Thermochemical pathways
  - Alcohol to Jet
- Plasma reformers
- Electric reformers
- Microwave reformers





Wismann et al., Science 364, 756–759 (2019)