NREL
Transforming ENERGY

Carbon Management and CO_2 Conversion

Josh Schaidle
Whole Value Chain CCUS
September 23, 2025

NREL at a Glance

4,026 Workforce, including:

- 2,968 regular/limited term
- 508 contingent workers
- 228 postdoctoral researchers
- 155 graduate student interns
- 167 undergraduate student interns

—as of 6/9/2025

World-class research expertise in:

- Energy Systems Integration
- Transportation and Fuels
- Buildings and Industry

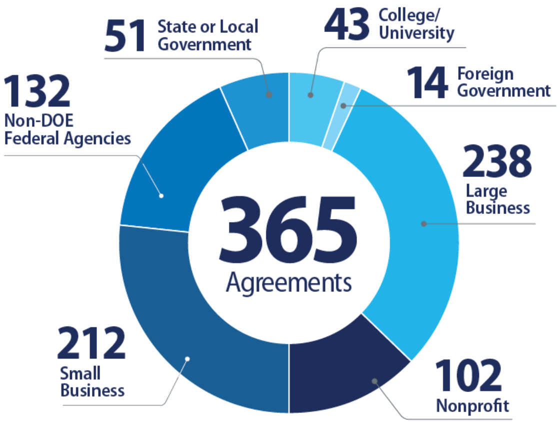
Partnerships with:

- Industry
- Academia
- Government

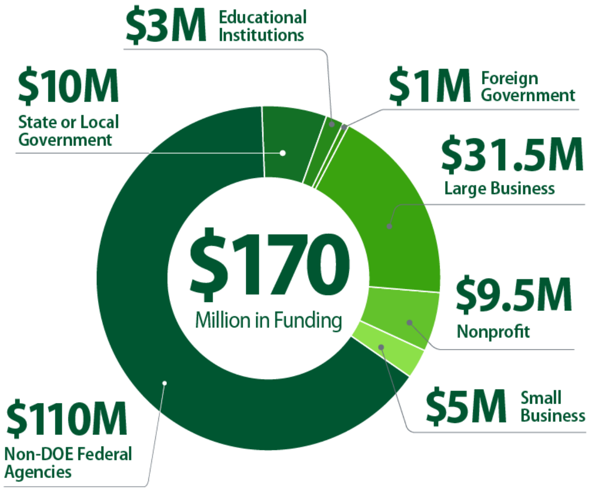
4 Campuses operate as living laboratories

Photo by Joe DelNero, NREL 89116

More Than 1,100 Active Partnerships in FY 2024



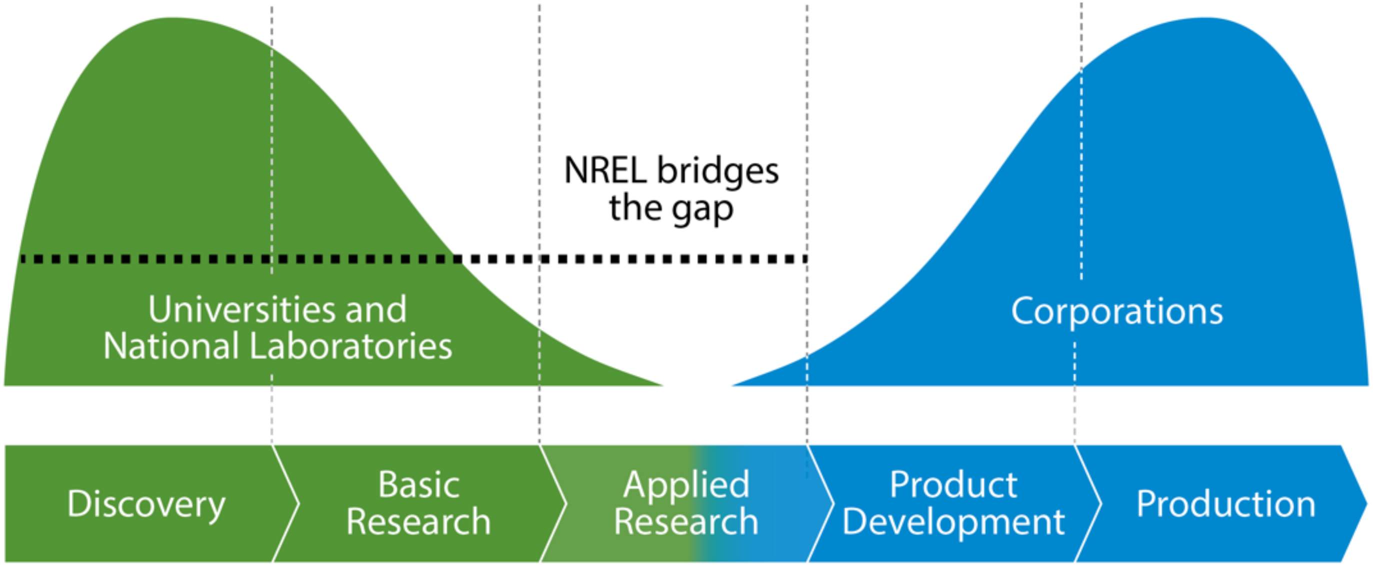
Agreements by Business Type



Funding by Business Type

*Due to agreements involving multiple partners, the number of partners exceeds the 365 new agreements executed in FY24.

We Reduce Risk in Bringing Innovations to Market



NREL helps bridge the gap from basic science to commercial application

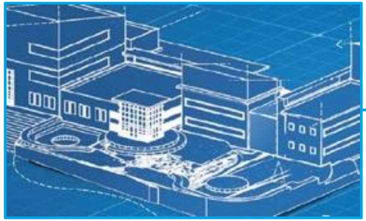
Forward-thinking innovation yields disruptive and impactful results to benefit the entire U.S. economy

Accelerated time to market delivers advantages to American businesses and consumers

NREL Brings Distinct Capabilities

Foundational Science	Accelerated Technology Scale-Up	Systems	Markets
Bench-scale- discovery	Scaling R&D and Process Engineering	R&D with Industry Partners	

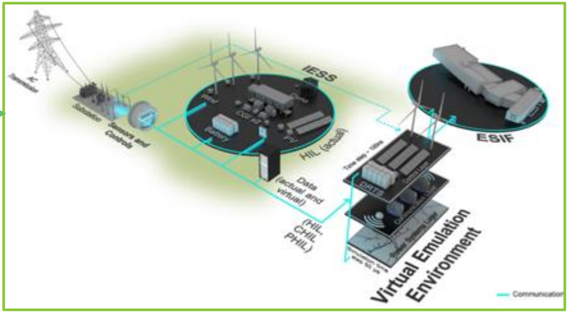
Solar Energy Research Facility
Science and Technology Facility
Field Test Laboratory Building



Energy Materials and Processing at Scale (Completion 2027)

Energy Systems Integration Facility

- Carbon-free H_2
- Grid and security tech
- Products from electrochemical processes and CO_2
- Advanced Batteries
- PV, Wind, Water Power, Geothermal
- New Buildings and Industrial Materials, Manufacturing and Systems



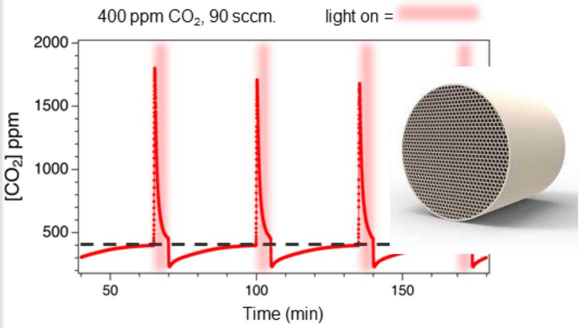
Advanced Research on Integrated Energy Systems (ARIES)

High-Performance Computing, Simulation, and Visualization

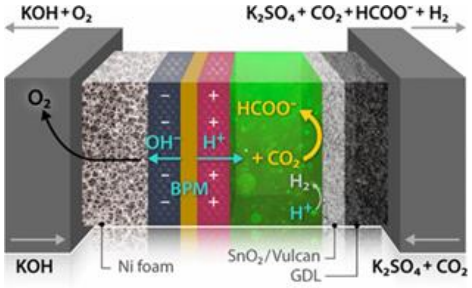
Our CCUS Portfolio is Responsive to Key Industry Needs

Technology Development

Photo-swing DAC

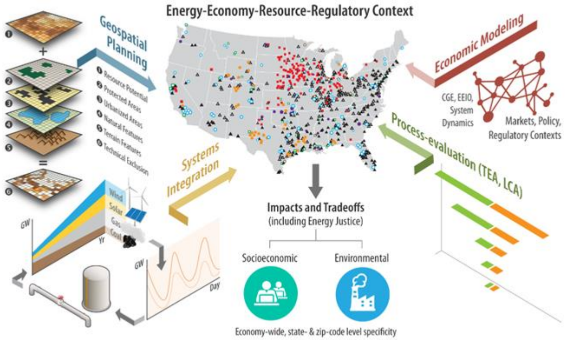


CO_2 Electrolysis Systems



Informed Deployment

Geospatially-explicit Decision Support



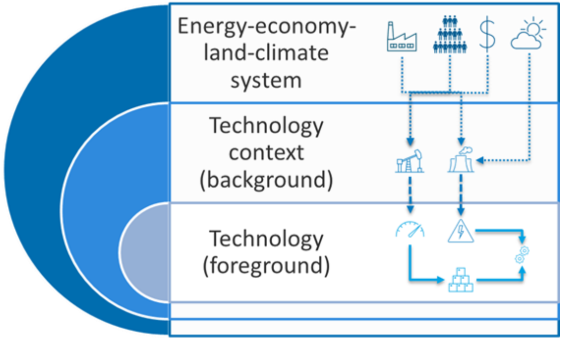
Integrated Process Demonstrations

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O$$

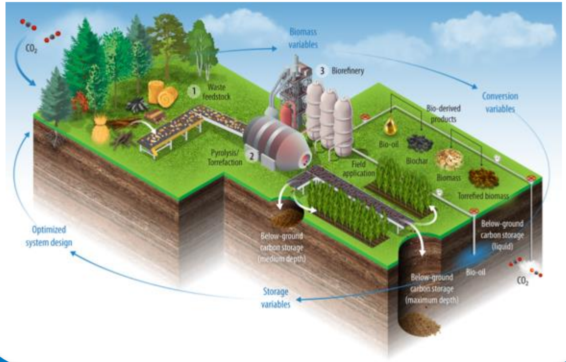
Biomethanation

Robust Accounting

Life-cycle Analysis



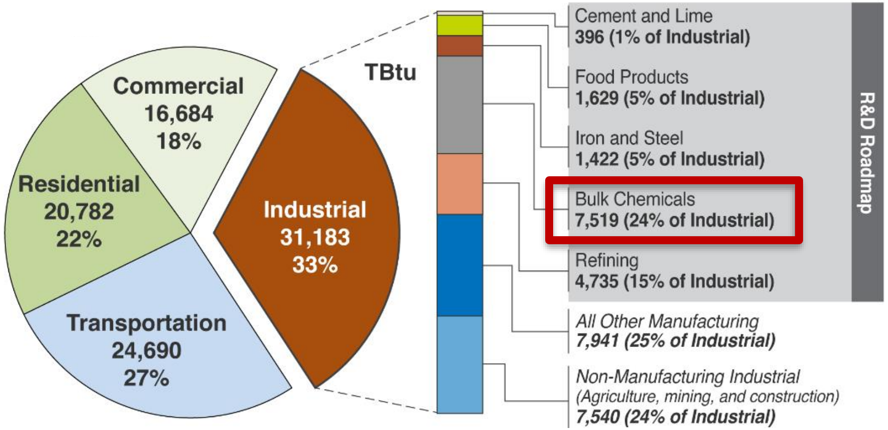
Biomass Carbon Removal and Storage



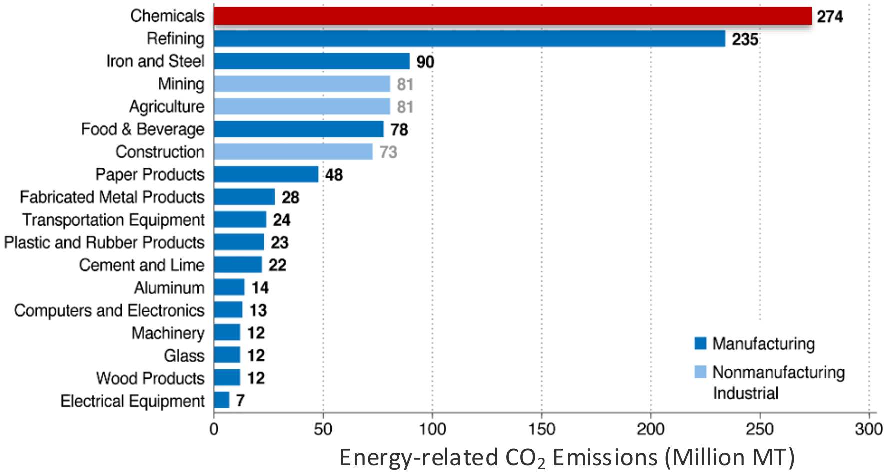
CO_2 Conversion

Energy Demand and Emissions in Industry

Energy Consumption



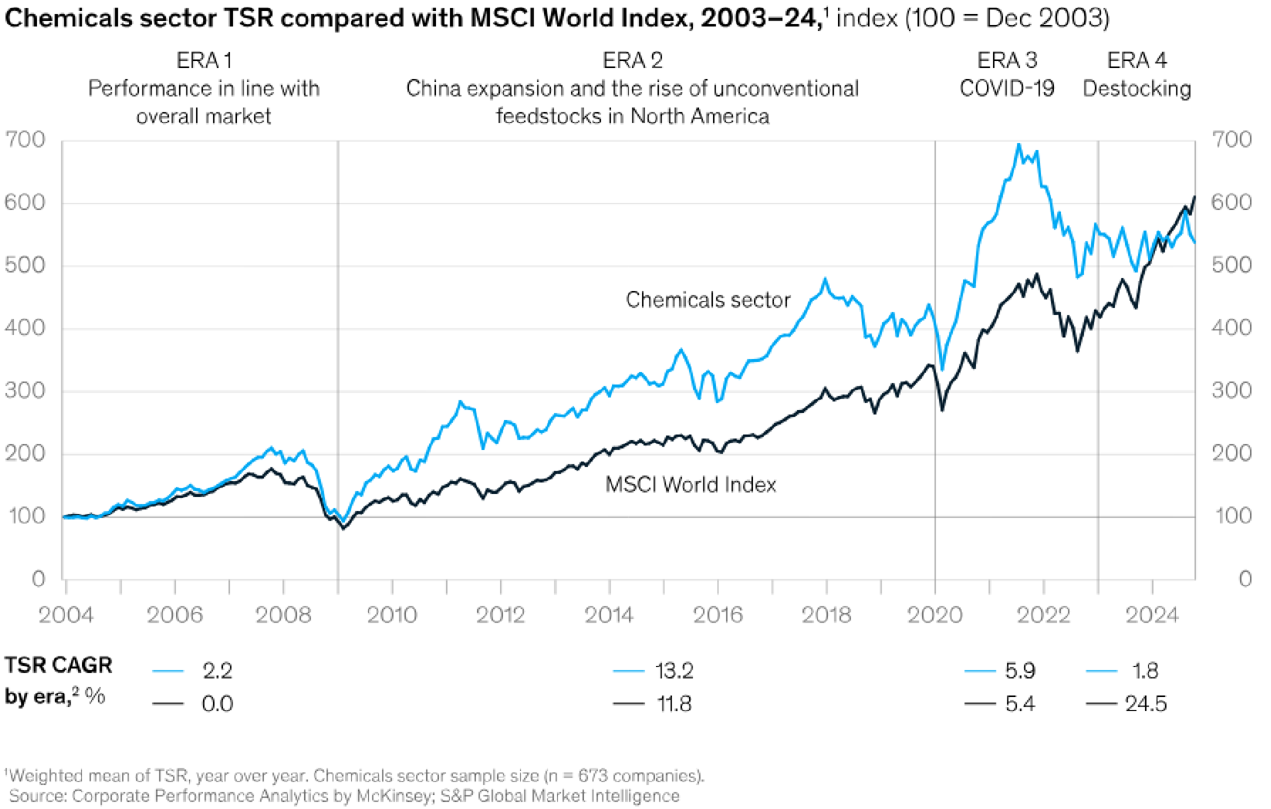
CO_2 Emissions



The US industrial sector consumes one third of US primary energy use and emits 30% of the total U.S. energy-related CO_2 emissions to deliver 10% of our GDP

U.S. DOE, Report DOE/EE-2635, September 2022

Challenge
Lagging Returns in the Chemicals Industry

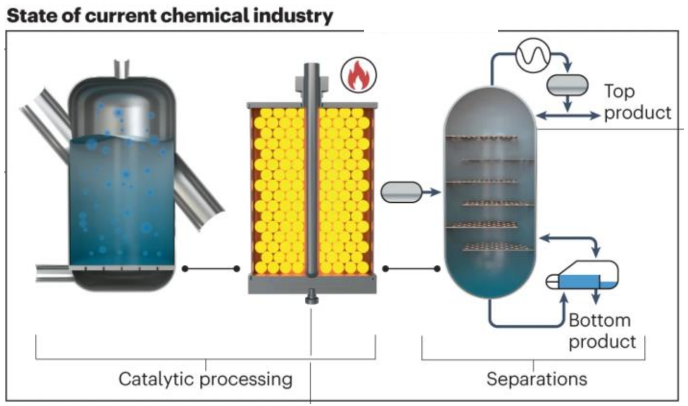


Key drivers:

- High energy prices
- Supply chain disruptions
- Interest rates and inflation
- Capacity addition exceeding demand growth
- Stalled innovation

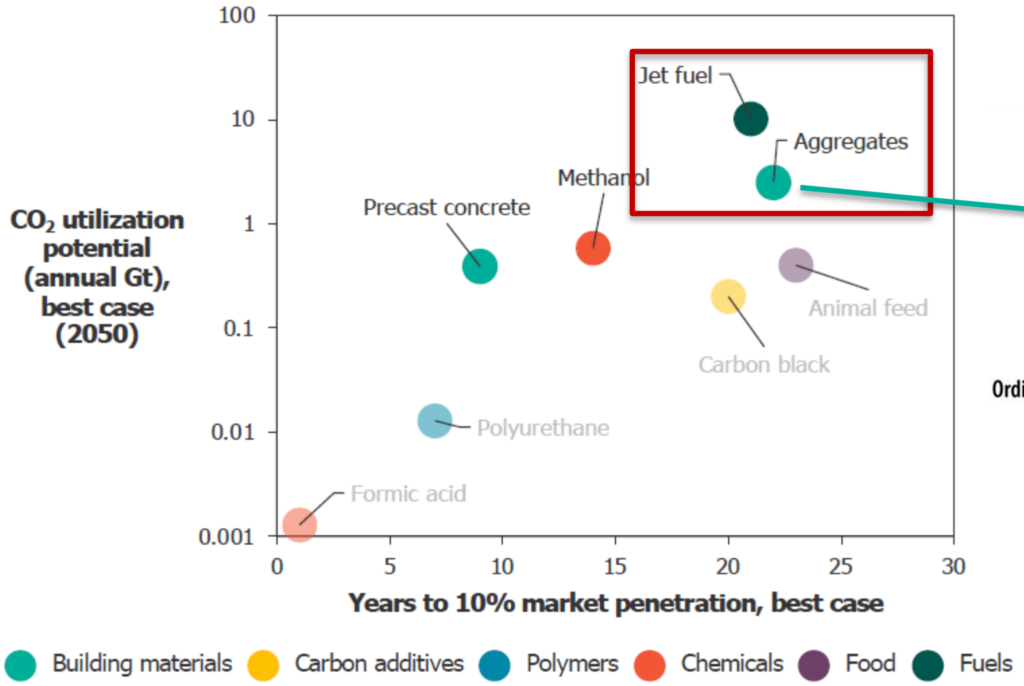
The State of the Chemicals Industry: Time for Bold Action and Innovation, McKinsey & Company, December 2024.

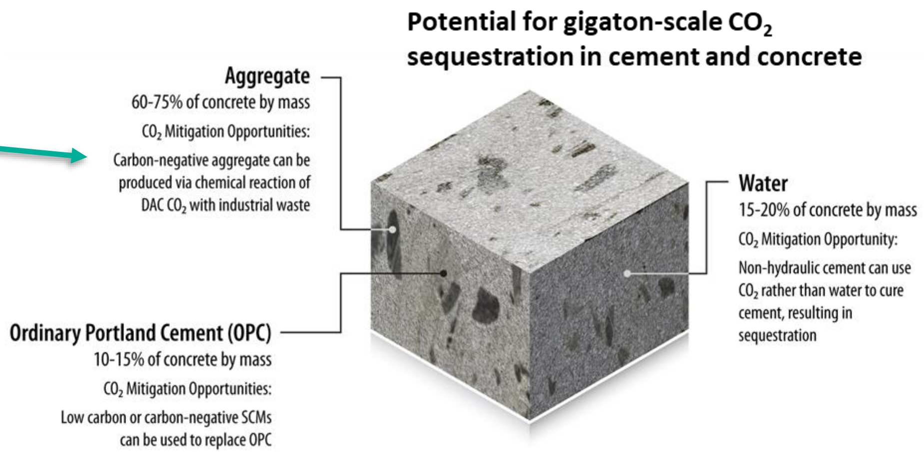
Opportunity
Chemical Manufacturing Innovation



Nature Reviews Chem 8 (2024) 376-400

Utilizing CO_2 could be a $1 Trillion Industry

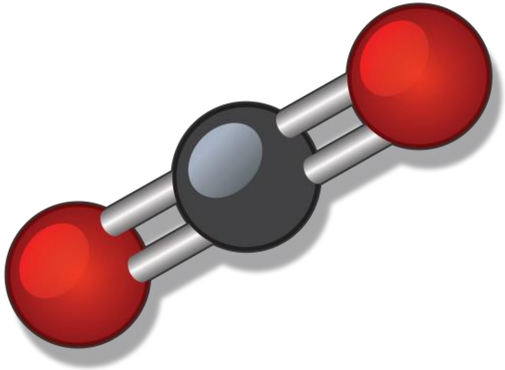




Implementing CO_2 Capture and Utilization at Scale and Speed, Global CO_2 Initiative, 2022

Brutal Reality of CO_2 Conversion to Fuel

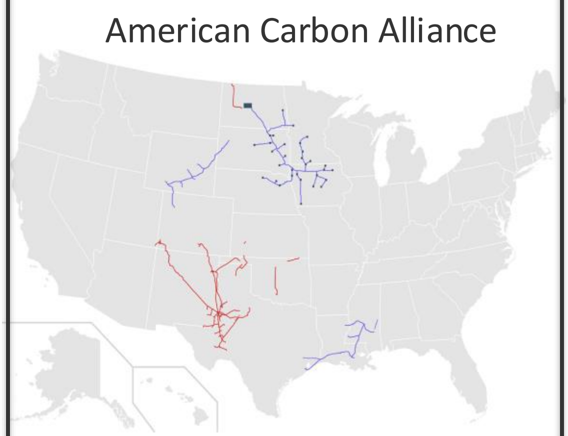
High Oxygen Content



And neither free nor pure

Requires Lots of Energy

Limited Pipeline Infrastructure



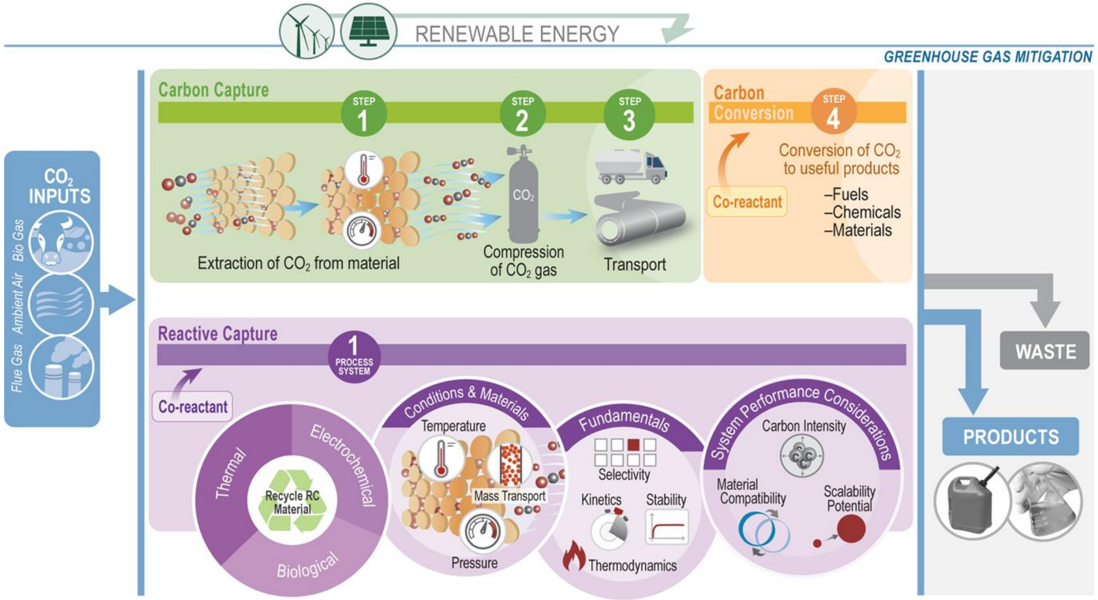
Innovation Opportunity: Reactive CO_2 Capture

Emerging Approach: Reactive Capture of CO_2

Reactive Capture Definition: The coupled process of capturing CO_2 from a mixed gas stream and converting it into a valuable product *without* going through a purified CO_2 intermediate

Can Include:

- Integration of CO_2 separation and conversion in one step
- Integration of separation and conversion in one unit
- Process intensification



Product Targets:

Form a valuable product, or mixture of products, in a more reduced state than CO_2

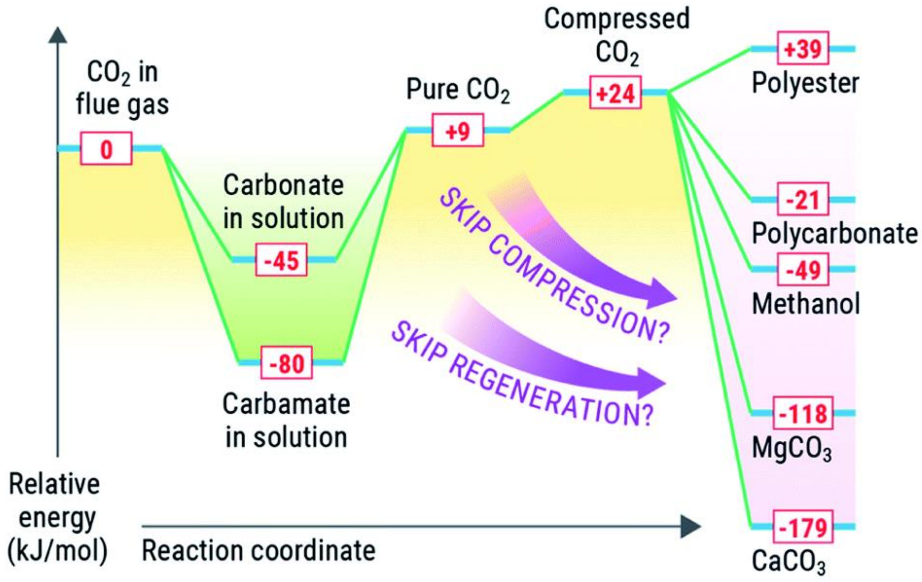
M. Freyman, et al., *Joule* 7 (2023) 631-651.

Proposed Value Proposition

Our proposed value proposition for reactive CO_2 capture is:

1. Lower energy intensity
2. Increased capital-expense-normalized productivity (i.e., capital utilization)

relative to the separate CO_2 capture and conversion processes that require a purified CO_2 intermediate.

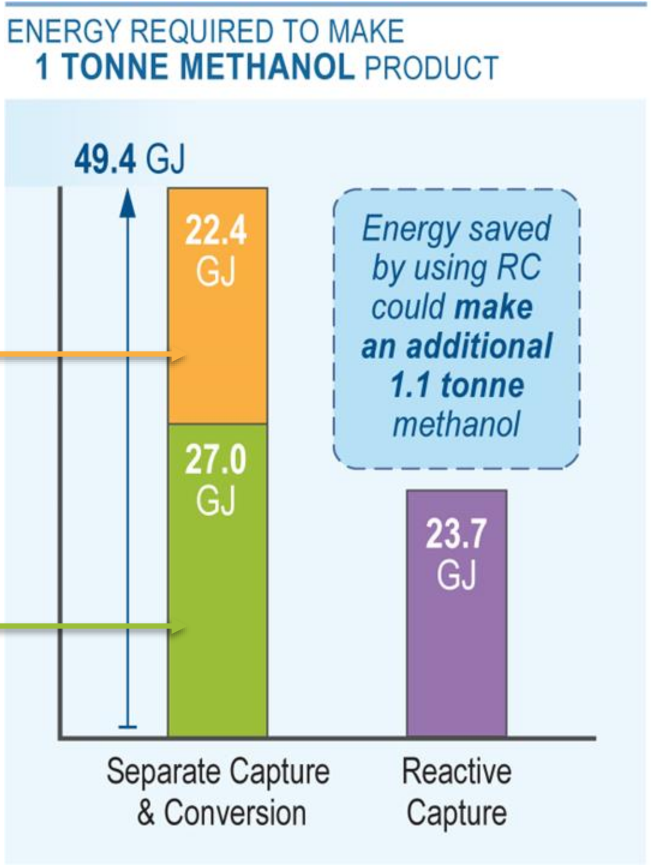


D. Heldebrant, et al., *Chem. Sci.* 13 (2022) 2445-6456

Value Proposition: Potential Savings

Conversion Energy

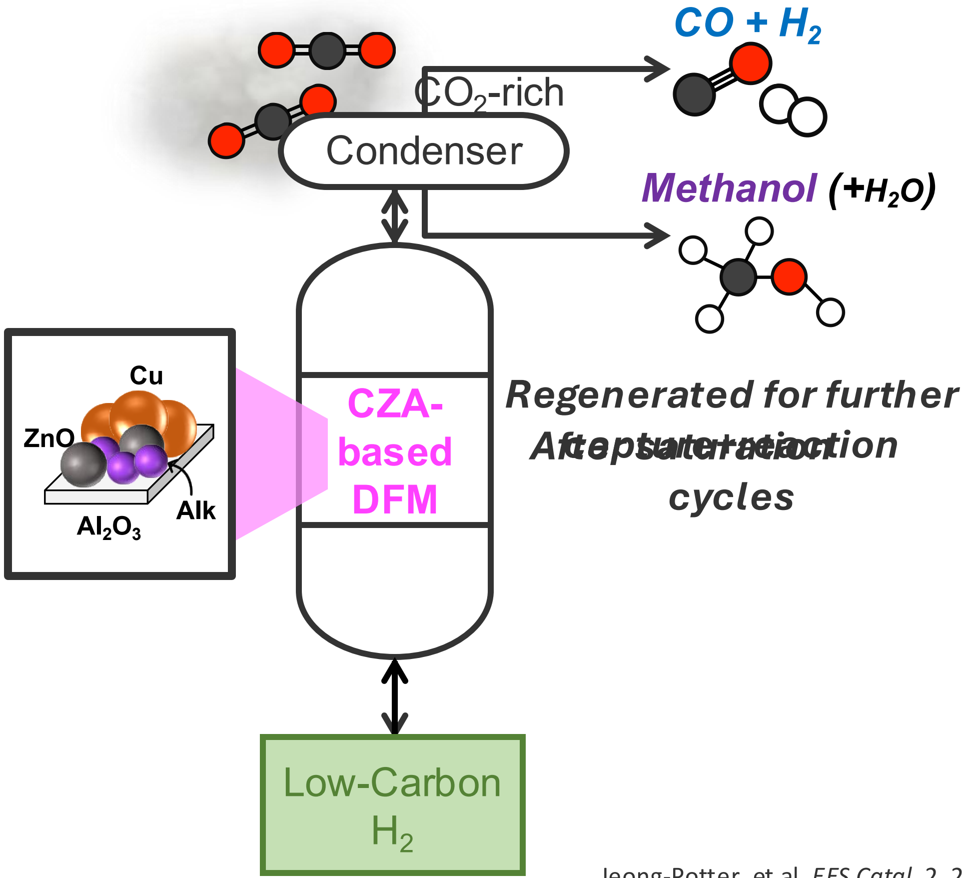
Capture Energy

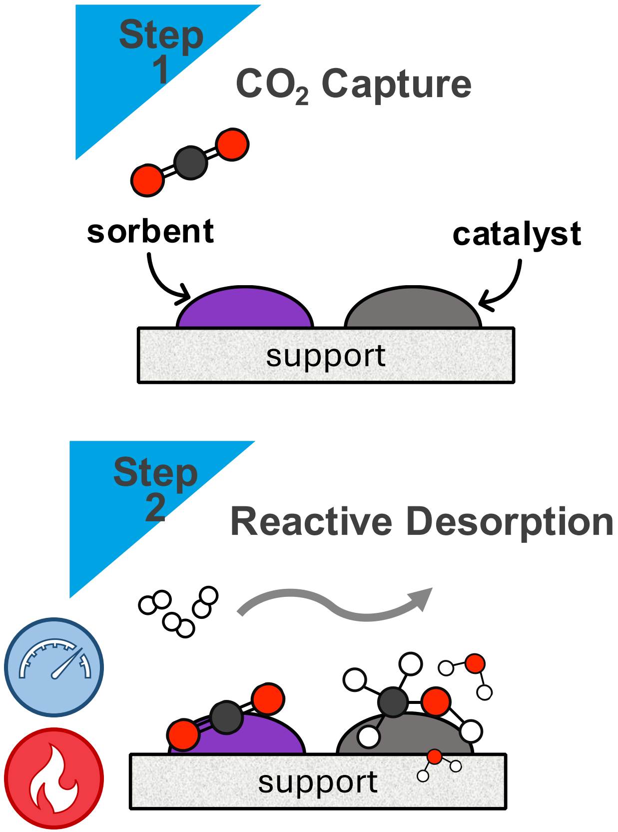


*Calculation assumes same methanol synthesis yield/efficiency regardless of CO_2 purity/captured state

Thermochemical Reactive CO_2 Capture

Reactive capture of CO_2 to MeOH – process concept

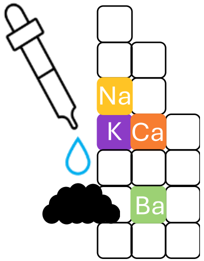


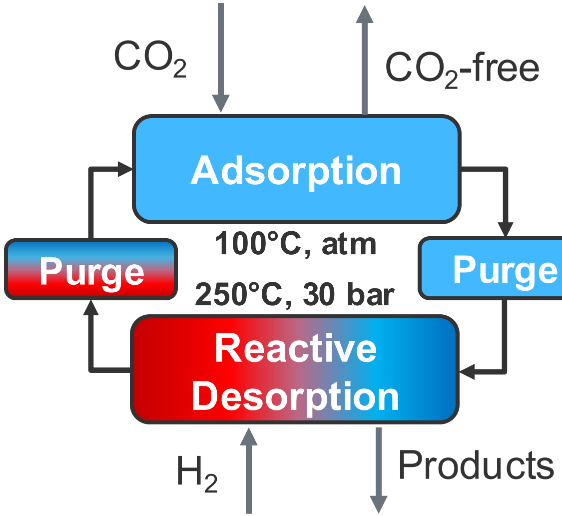


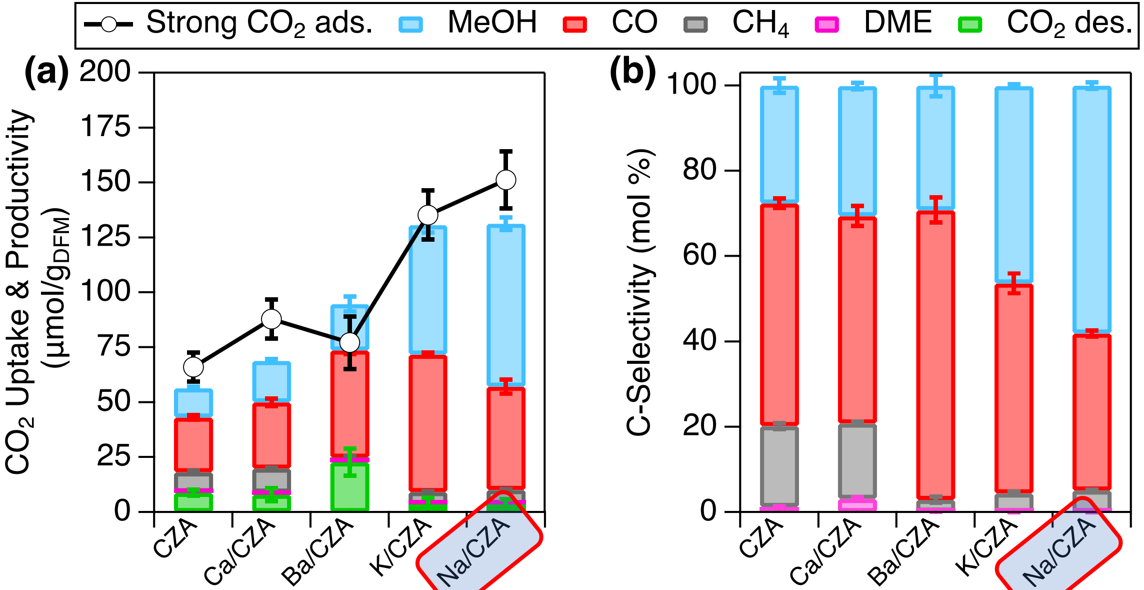
Jeong-Potter, et al. *EES Catal.* 2, 253 (2024).

Group 1 Alk-modification provides greatest benefit

Prepared by incipient wetness impregnation





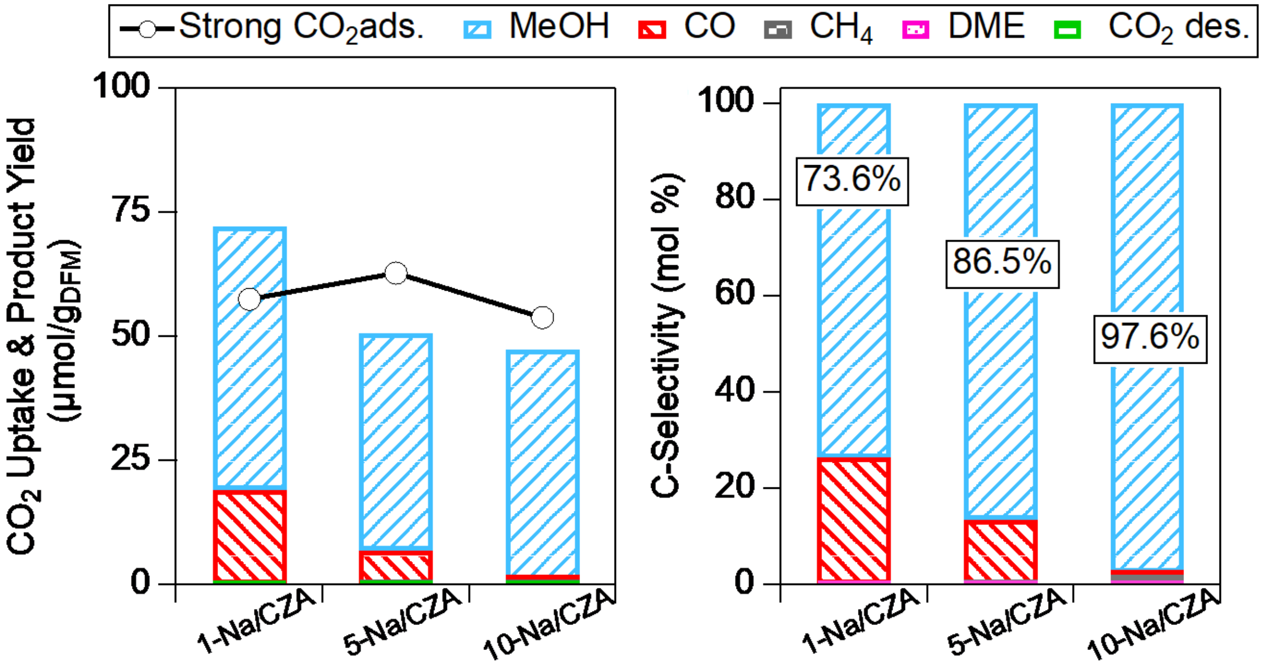


Each material was run for 5 RCC cycles, Data are average of the last 3 cycles

With highest capture capacity, MeOH selectivity and productivity, and low CH_4 selectivity, ***K/CZA and Na/CZA are the most promising materials***

Jeong-Potter, et al. *EES Catal.* 2, 253 (2024).

Effect of sorbent loading at "best conditions" (200°C, 30 bar)



*MeOH selectivity increased from **53% to 97%** with **5% increase** in MeOH productivity compared to starting point (5% Na/CZA, 250°C, 30 bar)*

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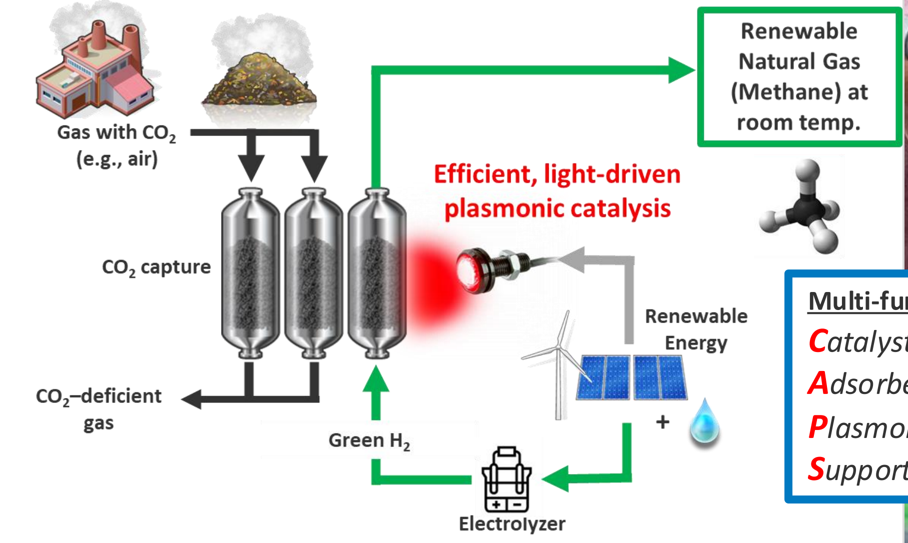
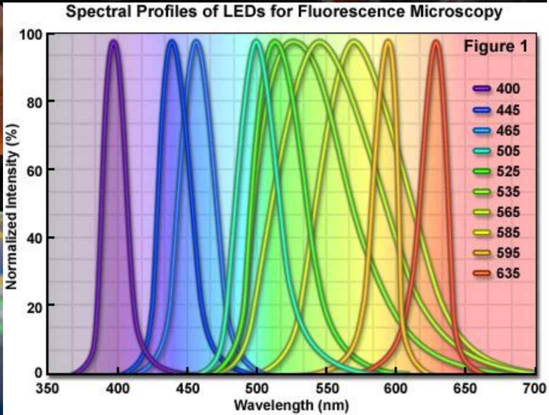
Photo-induced Reactive CO_2 Capture from the Atmosphere



Multi-functional material
Catalyst
Adsorbent
Plasmonic-antennae
Support



Background

Key Challenges for Reactive DAC

Mismatch of capture vs. catalysis conditions, sorbent degradation, component oxidation

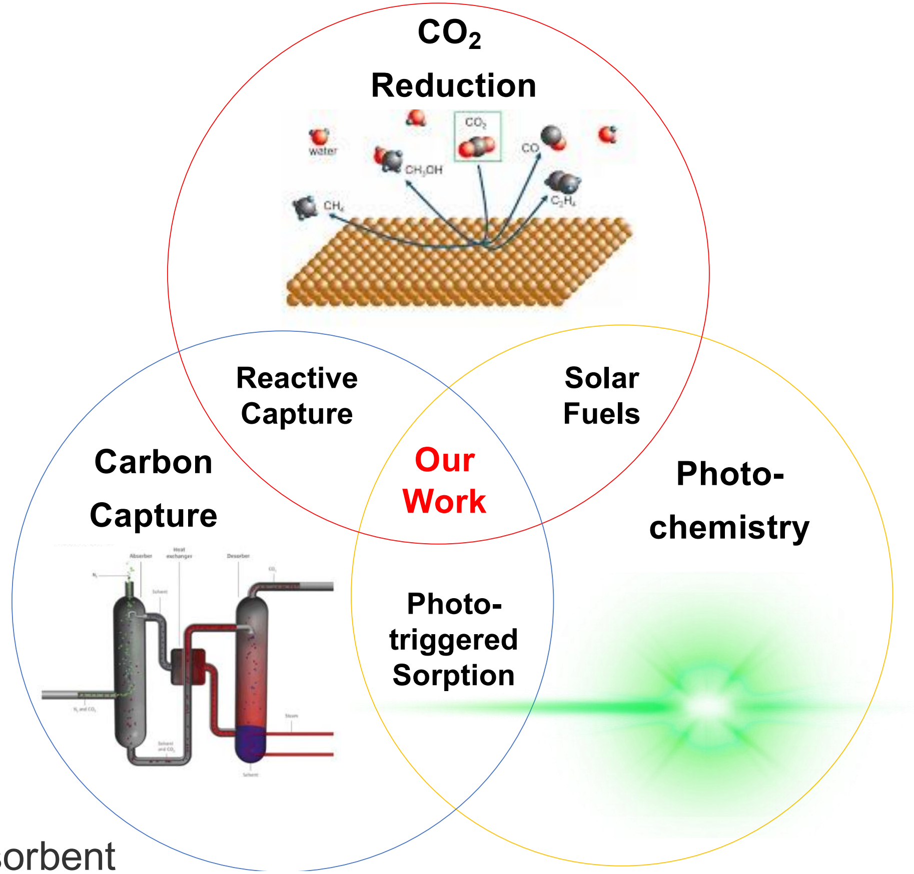
Hypothesis

Targeted radiation will eliminate need for bulk heating **AND** will enable catalysis at lower temperatures compatible with amine-based capture

Objectives

(1) Efficient photo-CO_2 release from commercial DAC sorbent

(2) Integrate CO_2 capture and conversion into a first-of-its-kind photoreactive amine-based DAC system



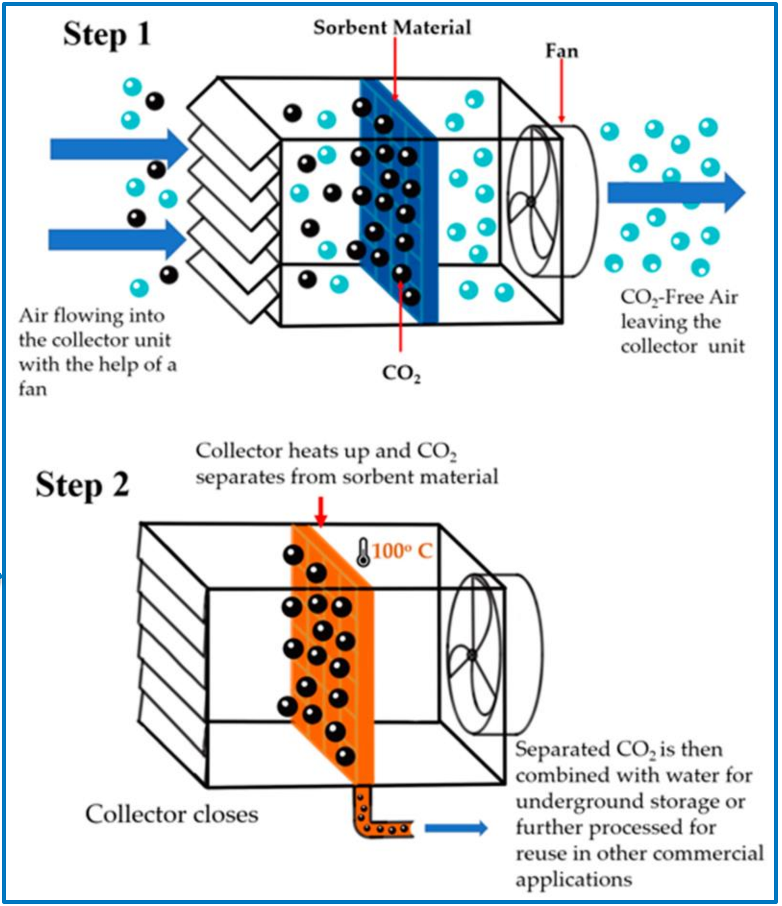
Our work is at the **NEXUS** of CO_2 reduction, Carbon Capture, and PhotoChemistry

Direct Air Capture (DAC)

Remove dilute streams of CO_2 (400 ppm) from the atmosphere.

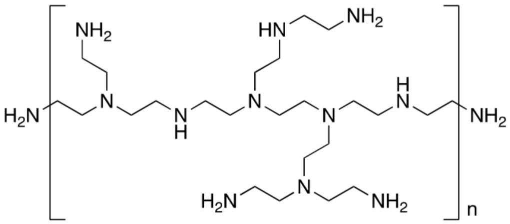
The two mainstream technologies are based on:

- liquid solvents
- **solid sorbents**

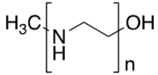


Garza, D.; Dargusch, P.; Wadley, D. A Technological Review of Direct Air Carbon Capture and Storage (DACCS): Global Standing and Potential Application in Australia. Energies 2023, 16, 4090. https://doi.org/10.3390/en16104090

Polyethyleneimine (PEI) as CO_2 DAC sorbent

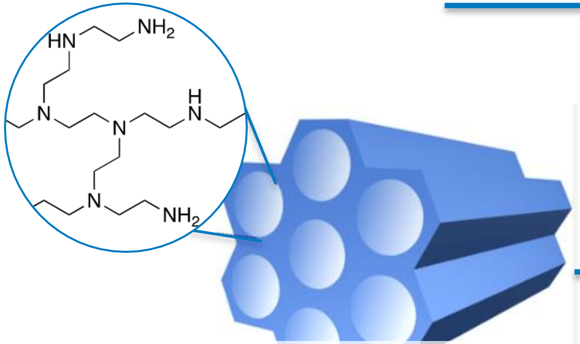


Branched PEI

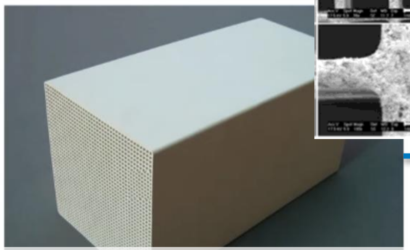


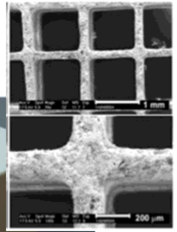
Linear PEI

- Adsorption enthalpies ideal for dilute CO_2 streams
- Commercially available
- Low volatility



Composite CO_2 sorption materials





PEI impregnated contactor

Courtesy of Global Thermostat

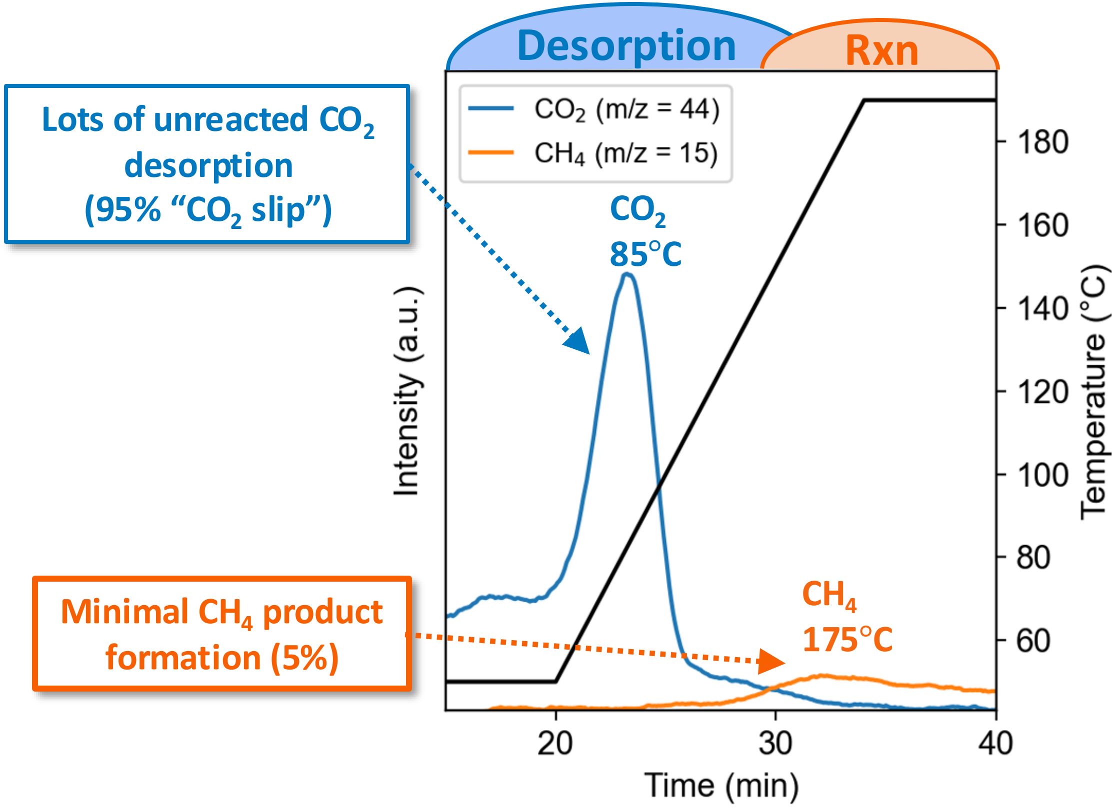
Pilot plan with a capacity
> 1,000 tons of CO_2/years

Global Thermostat: https://www.globalthermostat.com/news-and-updates/global-thermostat-colorado-headquarters

CO_2 Slip in Thermally Driven Reactive Capture with Amines

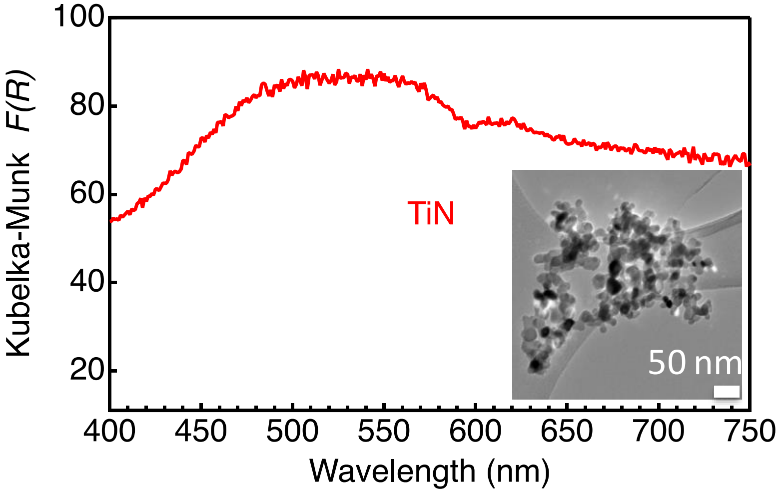
To date, temperature-driven conversion requires bulk temps. ~175 °C, posing two challenges:

- CO_2 ”slip”: adsorbed CO_2 desorbs ~85 °C
- -NH_x degradation: amino-polymers start degrading ~120 °C



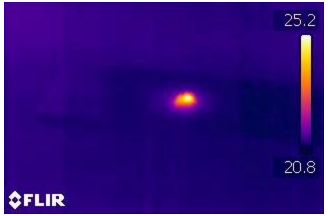
Bulk TiN particles – plasmonic heating

Bulk TiN particles –
UV-Vis absorbance and TEM picture

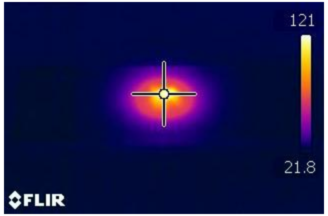


Bulk TiN particles - 10 mg sample on glass slide, N_2 atmosphere, 625 nm LED w/ focusing lens

Current to LED (mA)	Measured Irradiance (mW/cm^2)	Bulk Sample Temp. °C Measured @ 2 min.
23	10	26
210	100	57
700	320	120



10 mW/cm^2



320 mW/cm^2

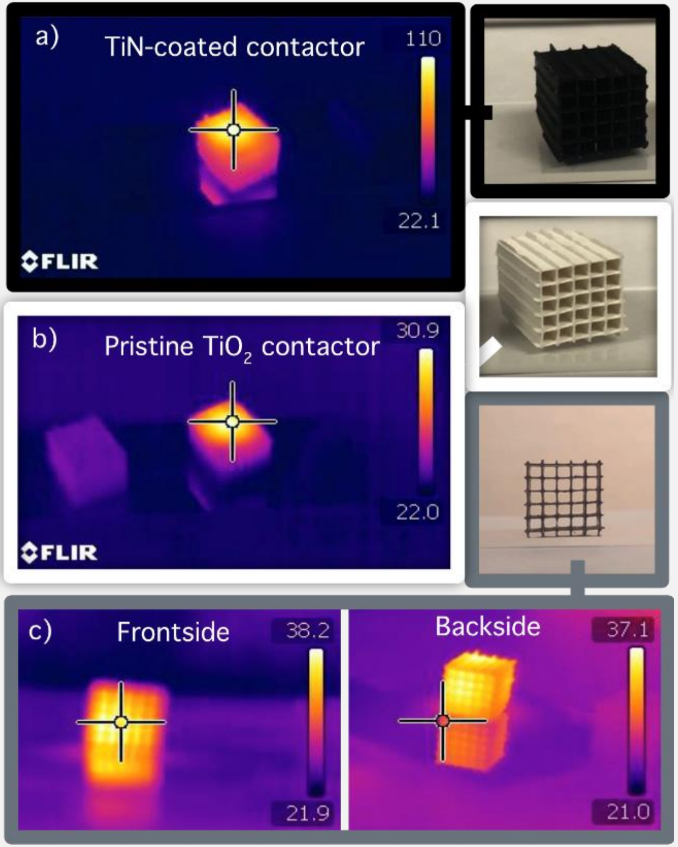
TiN as the photo-responsive material

Current to LED (mA)	Measured Irradiance (mW/cm²)	Bulk Sample Temp. °C Measured @ 2 min.
23	10	26
210	100	46
700	320	94

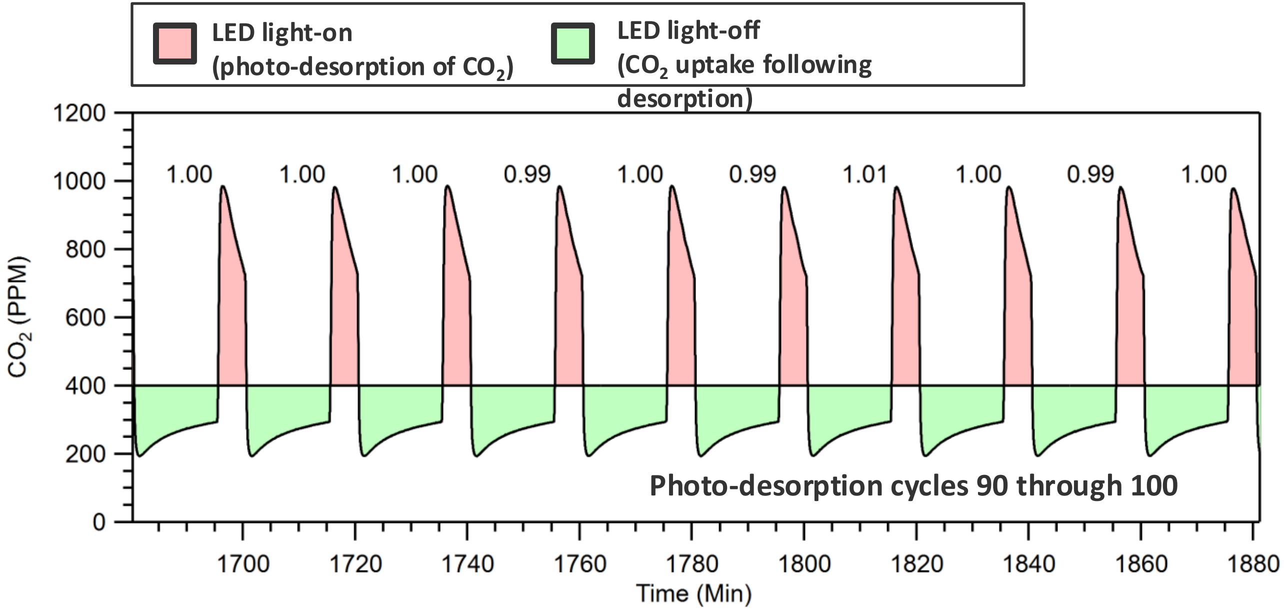
Photo-induced heating is compatible with amines

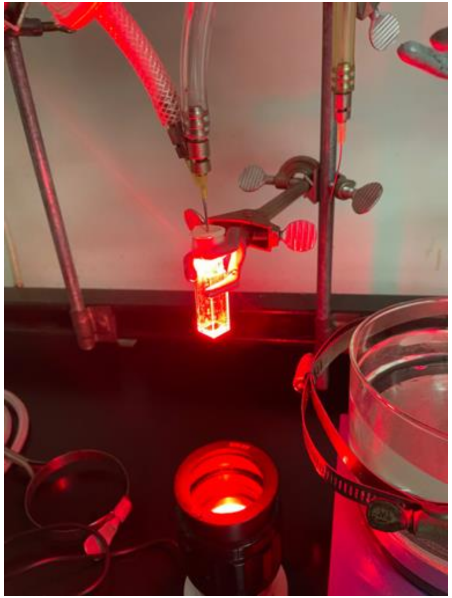
2.5 wt% TiN in ~1:1 PEI:Al_2O_3

N_2 atmosphere, 625 nm set to 700 mA LED w/ focusing lens



Demonstrated Photo-thermal Swing Adsorption





- Efficient photo-desorption without amine degradation

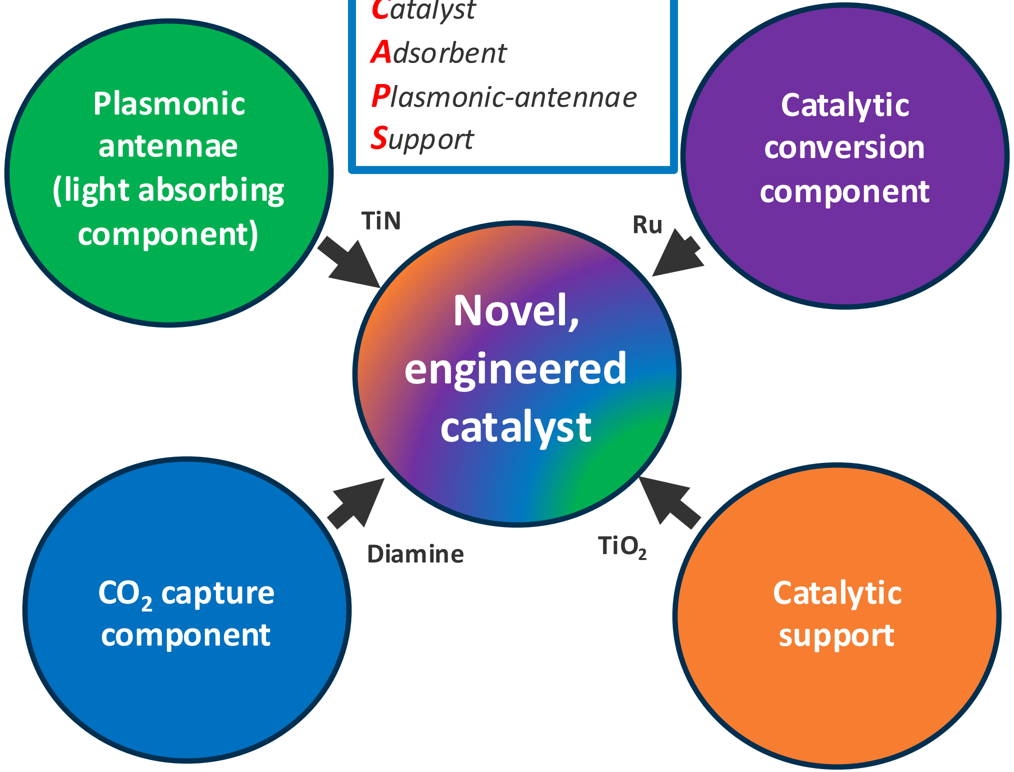
Use electrified LED lighting to replace thermal (steam) heating for CO_2 desorption

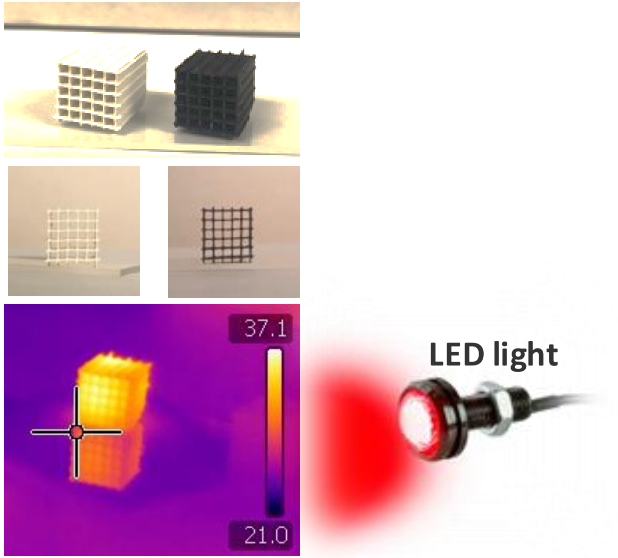
Material: Amine + Titanium Nitride + Monolith Contactor
Conditions: 400 ppm CO2 constant flow
Irradiance with 625 nm LED light

Multi-function “CAPS” material for photo-induced reactive DAC

Multi-functional catalyst

Catalyst
Adsorbent
Plasmonic-antennae
Support





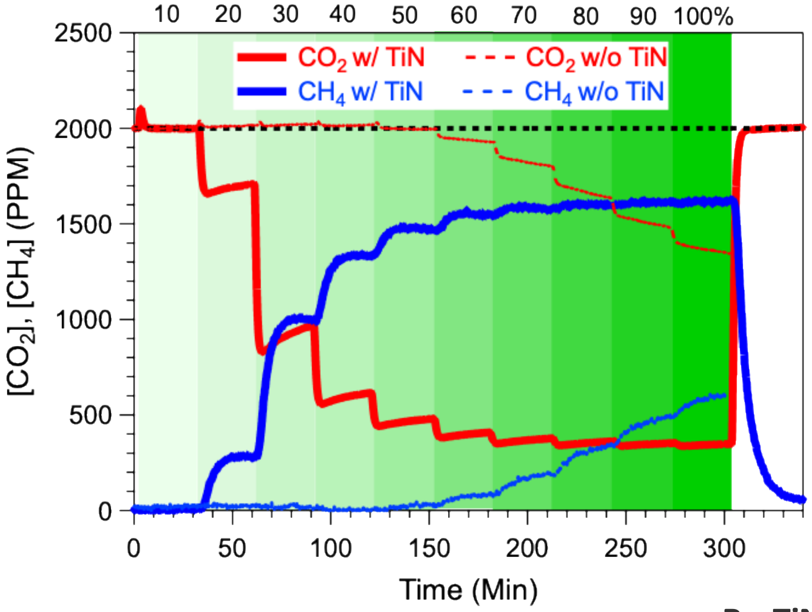
Monolith impregnated with TiN for light absorption

Photo-induced methanation (steady-state and pulsed)

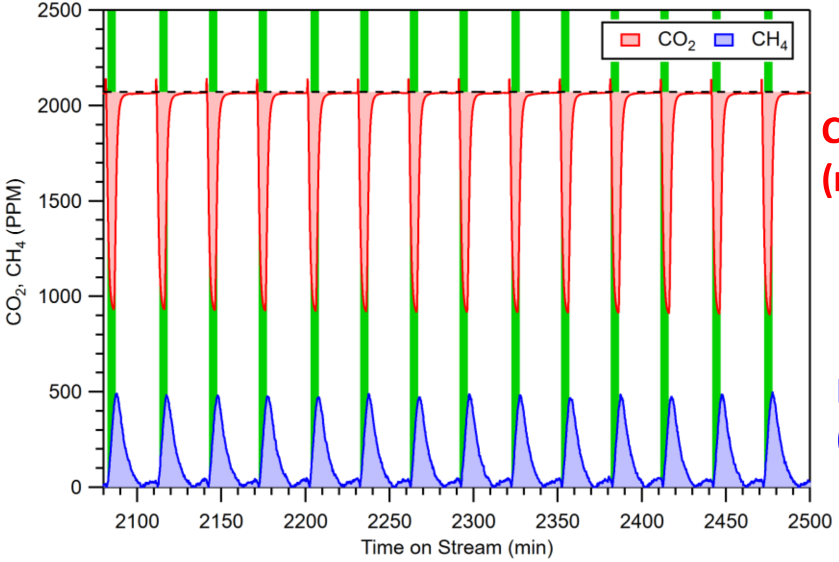
Methanation:

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$$

<u>Steady-state</u> photo-methanation



<u>Pulsed</u> photo-methanation



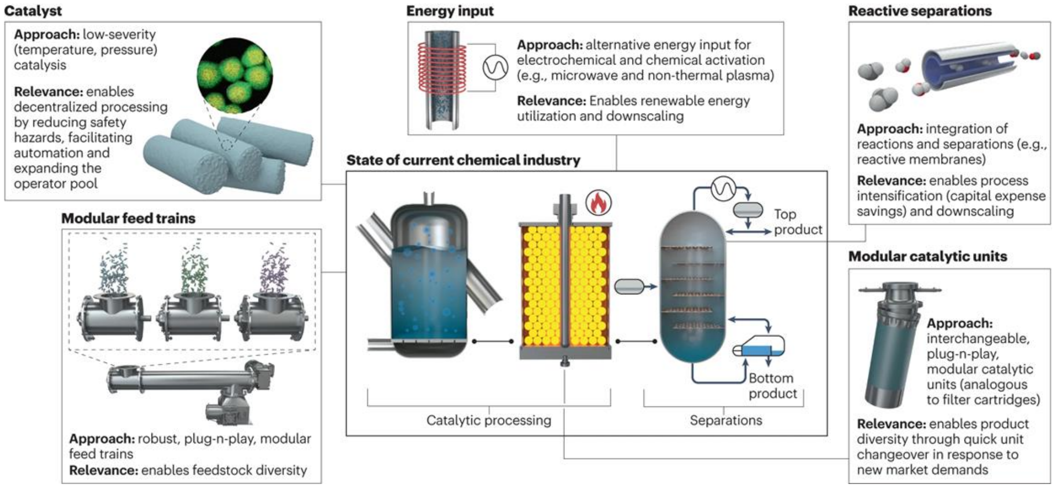
CO_2 (reactant)

Methane (product)

Ru-TiN-diamine-TiO_2

Summary and Conclusions

- The industrial sector is **complex, diverse, and energy intensive**
- **Innovation** can be a differentiator
- **CO_2 utilization** presents a significant future opportunity, but is expensive today
- **Reactive CO_2 capture, coupled with alternative energy input strategies**, is at an early-stage of development and provides a means to reduce cost and energy intensity



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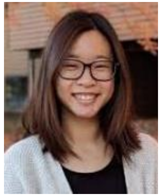
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U.S. DEPARTMENT OF ENERGY • OFFICE OF FOSSIL ENERGY

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CHANGING WHAT'S POSSIBLE

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BIOENERGY TECHNOLOGIES OFFICE

OTT
Office of Technology Transitions

NREL Laboratory Directed Research and Development (LDRD) Program

Let's Discuss!

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