THE LLNL CARBON INITIATIVE

Carbon Conversion at LLNL: Overview and Perspective

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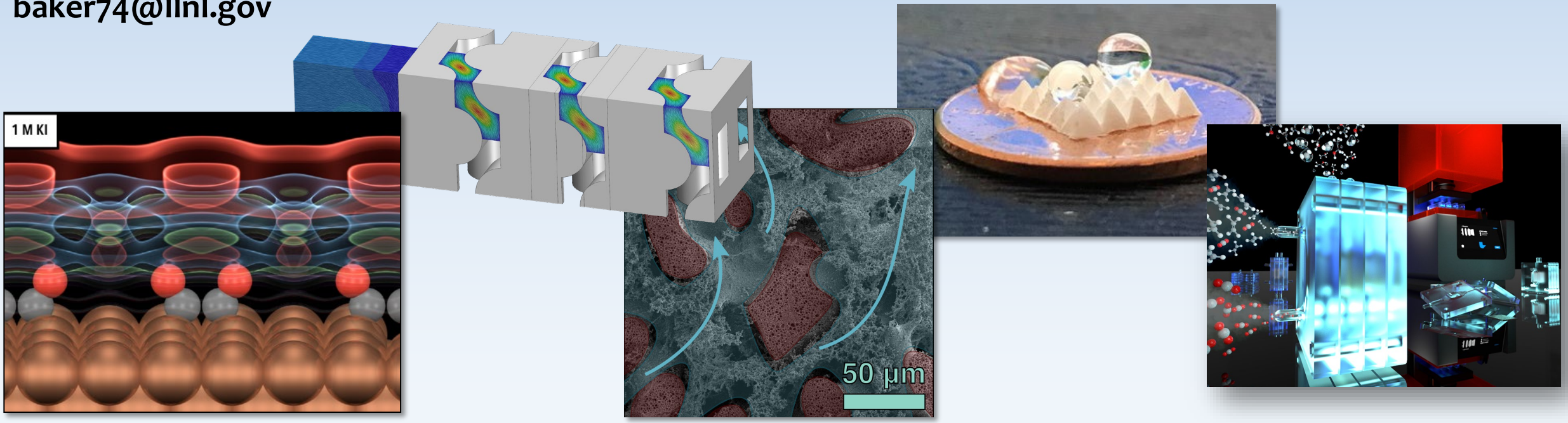


Prepared by LLNL under Contract DE-AC52-07NA27344.

Carbon dioxide conversion can create clean manufacturing industries in California

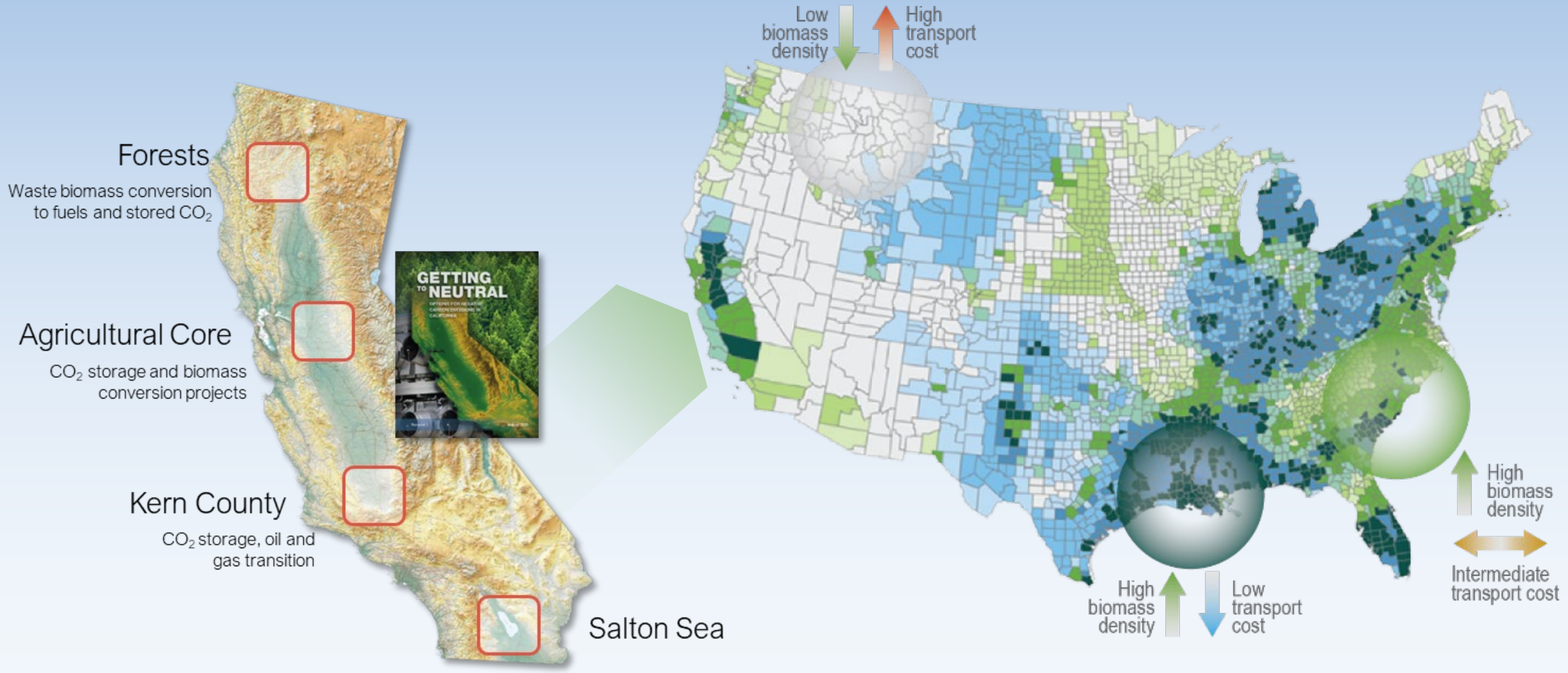
Steam cracking to produce ethylene

- High temperatures and pressures [500-700° C and 150-250 kPa (20-40 psi)]
- Only economical at large scale
- ~1.5 fossil derived CO_2 emitted per molecule ethylene
- Located at shale gas site
- Not flexible, cannot use renewable energy efficiently

CO_2 electrolysis to ethylene

- Low temperatures and pressures (30-70° C at atmospheric pressure)
- Modular systems scale up and down
- Potential for carbon neutral ethylene, depends on source of CO_2 and energy
- Located at waste CO_2 source, highly distributed (see map above)
- Highly amenable to utilizing (intermittent) renewable electricity

California's Climate Goals can help Create a Carbon Conversion/Removal Ecosystem (CO_2 supply, transportation networks)



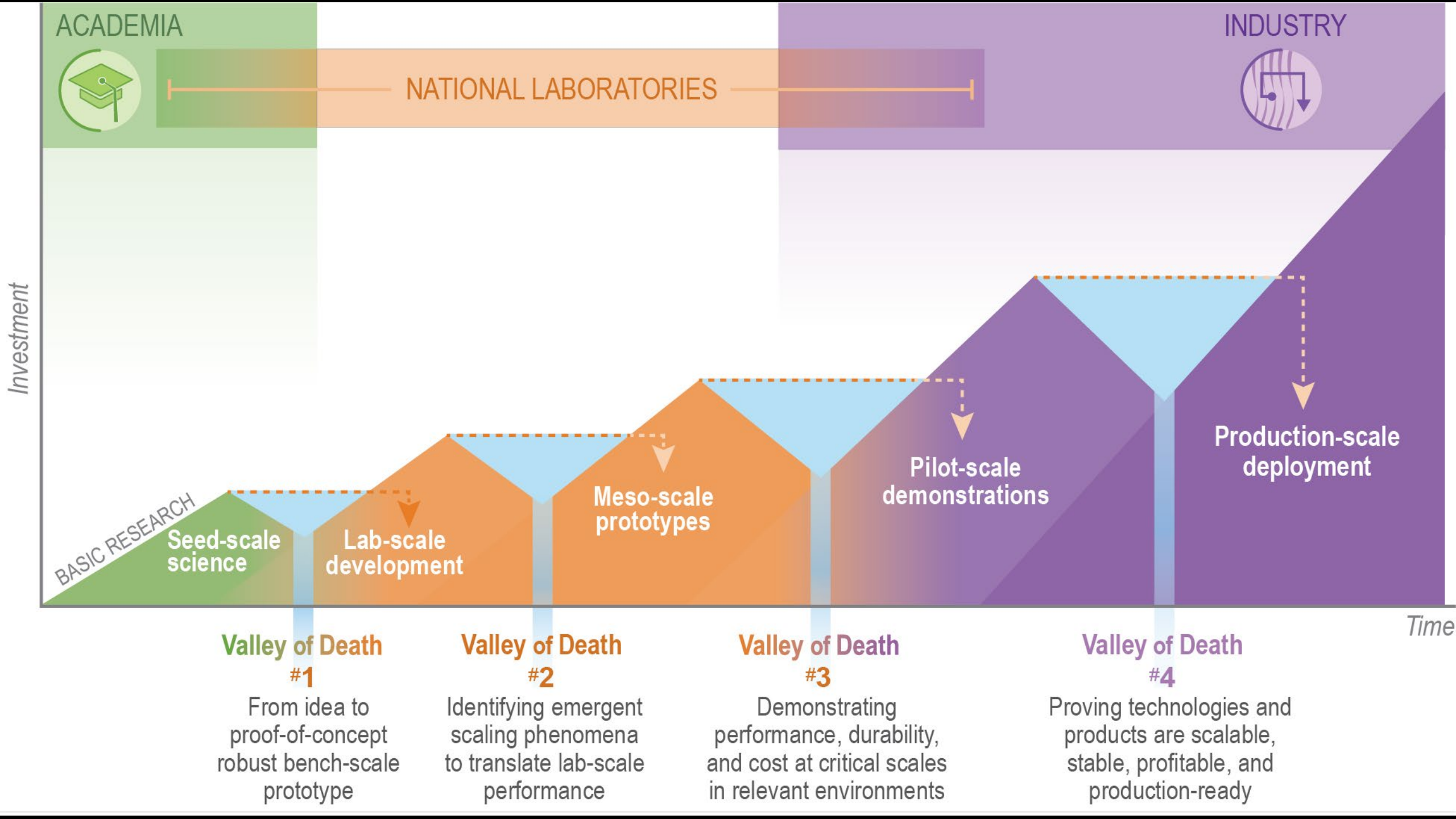
National Labs Can Help Create CO_2 Conversion Ecosystem

-Supply chain

-Workforce

-Colocation challenge: CO_2 source, renewable electricity source, product offtake

-Early partnership/bridge between technology developer and customer


ACADEMIA
NATIONAL LABORATORIES
INDUSTRY
Investment
BASIC RESEARCH
Seed-scale science
Lab-scale development
Meso-scale prototypes
Pilot-scale demonstrations
Production-scale deployment
Time
Valley of Death #1
From idea to proof-of-concept robust bench-scale prototype
Valley of Death #2
Identifying emergent scaling phenomena to translate lab-scale performance
Valley of Death #3
Demonstrating performance, durability, and cost at critical scales in relevant environments
Valley of Death #4
Proving technologies and products are scalable, stable, profitable, and production-ready

LLNL Carbon Management Technology Development Focus Areas

Top-down design of carbon capture and DAC materials and structures

Improving mass and heat transport for catalysis and separations

Electrifying thermal processes

Designing material for scalable manufacturing

Rapid prototyping

High performance electrolyzer components

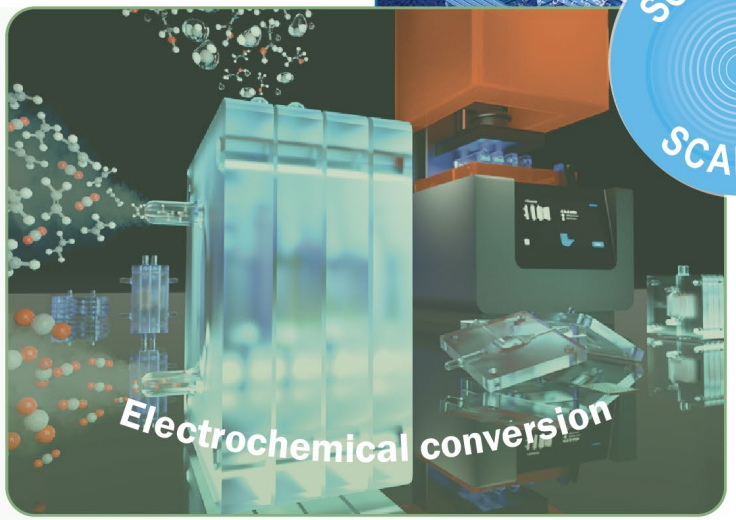
Bubble management

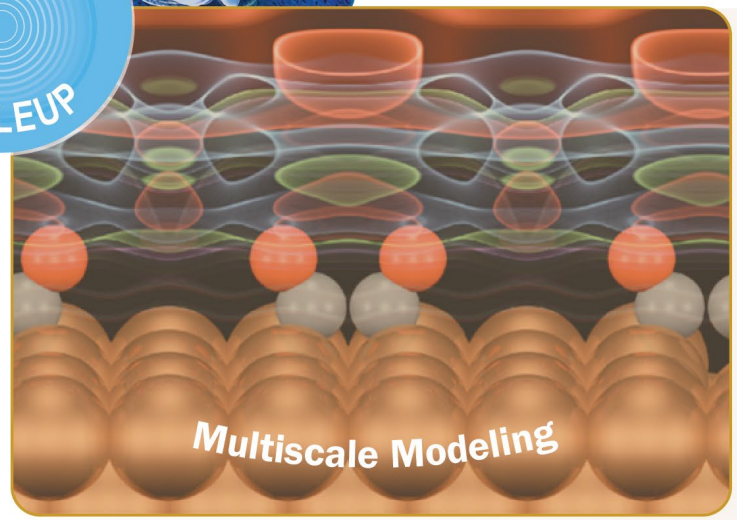
SCIENCE OF SCALEUP

Co-electrolysis and reactive capture

New reactor designs

Electrification of chemical manufacturing



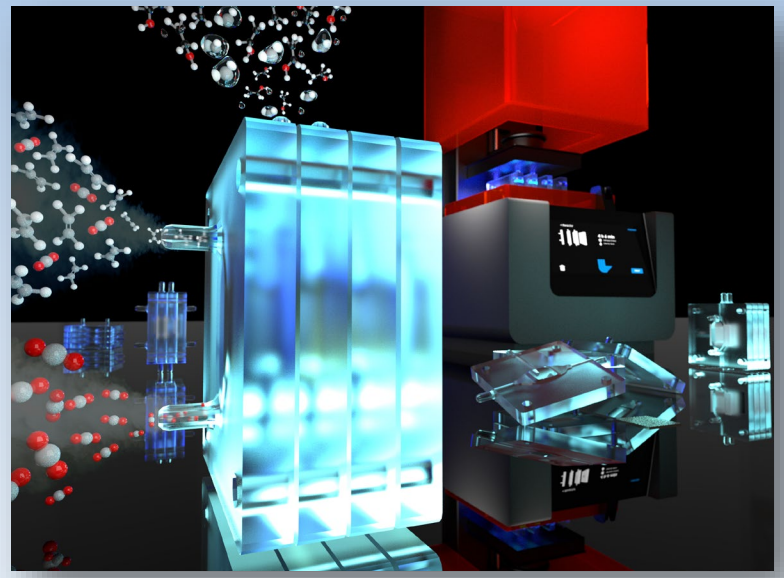


Design for durability: DAC adsorbents and ion exchange membranes

Continuum to system level modeling for design and operation

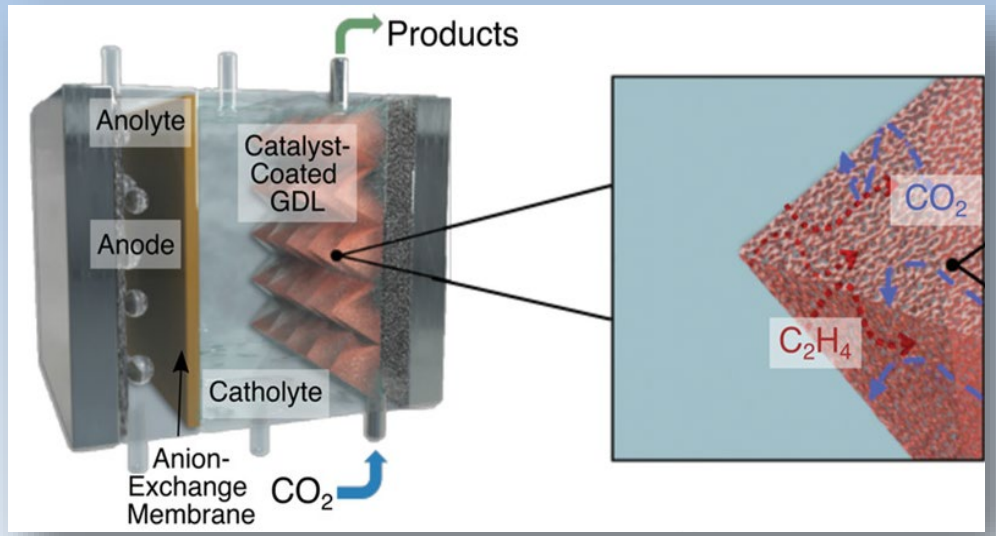
Electrochemical interface theory

Demonstrating Advanced Manufacturing to Improve Performance in Electrochemical Conversion of CO_2



Rapid prototyping of electrolyzer housing leads to highest reported yields for ethanol

Corral, D., Feaster, J.T., et al., *Energy Environmental Science* (2021).



Porosity and structural control of gas diffusion layers leads to order of magnitude improvements in C-C coupling

Wicks, J., Jue, M.L., Beck, V.A., et al. *Advanced Materials*, 33, 2003855 (2021).

Printed electrodes enable highest reported productivity for electrified bioreactors

Kracke, F., Jayathilake, B.S., et al. *Frontiers in Microbiology*, 12 (2021).

Current carbon utilization partnerships at LLNL

ACADEMIA

Stanford University

UNIVERSITY OF CALIFORNIA SANTA CRUZ

UCMERCED UNIVERSITY OF CALIFORNIA

UCDAVIS UNIVERSITY OF CALIFORNIA

UNIVERSITY OF CALIFORNIA

UC NATIONAL LABORATORY FEES RESEARCH PROGRAM

NATIONAL LABS

BERKELEY LAB

NREL Transforming ENERGY

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT WHERE INNOVATION BEGINS

GOVERNMENT

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

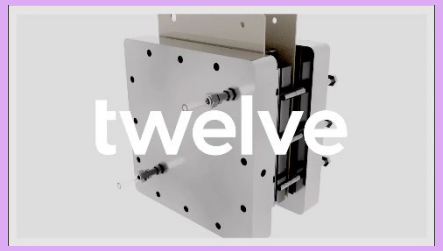
U.S. DEPARTMENT OF ENERGY | Office of Technology Transitions

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

INDUSTRY

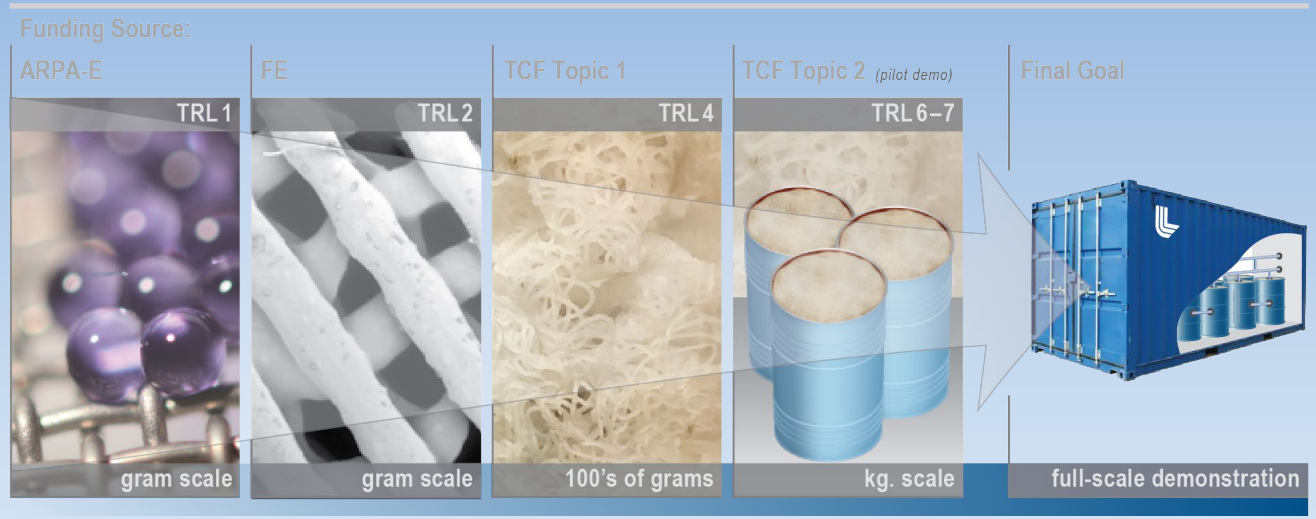
TotalEnergies



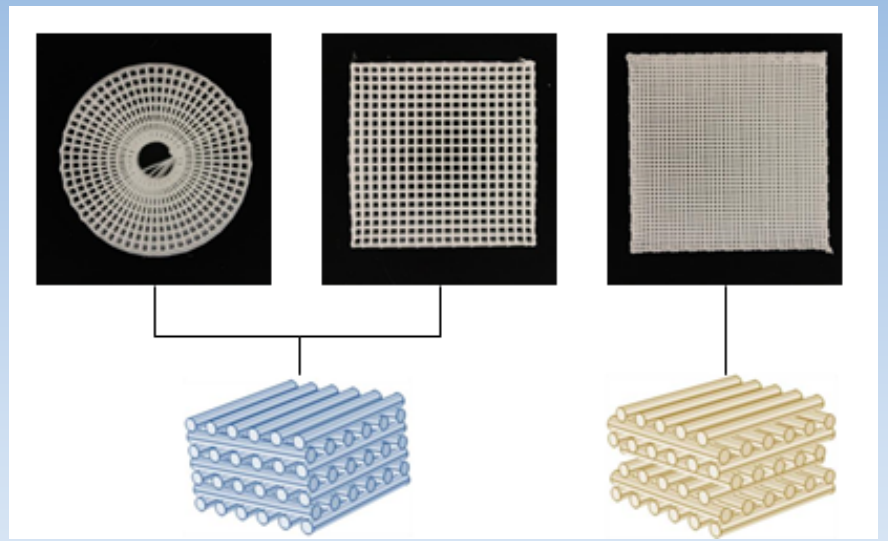
SIEMENS energy

SoCalGas

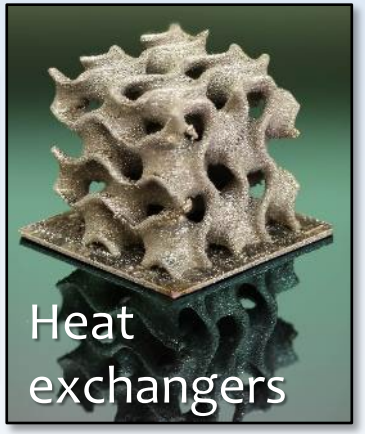
LLNL's Carbon Capture and Carbon Removal Program

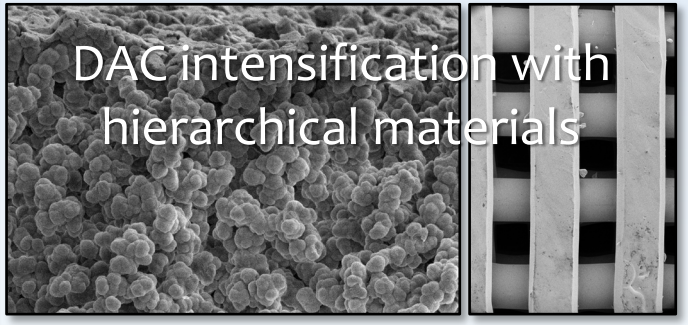


Microencapsulation with advanced solvents



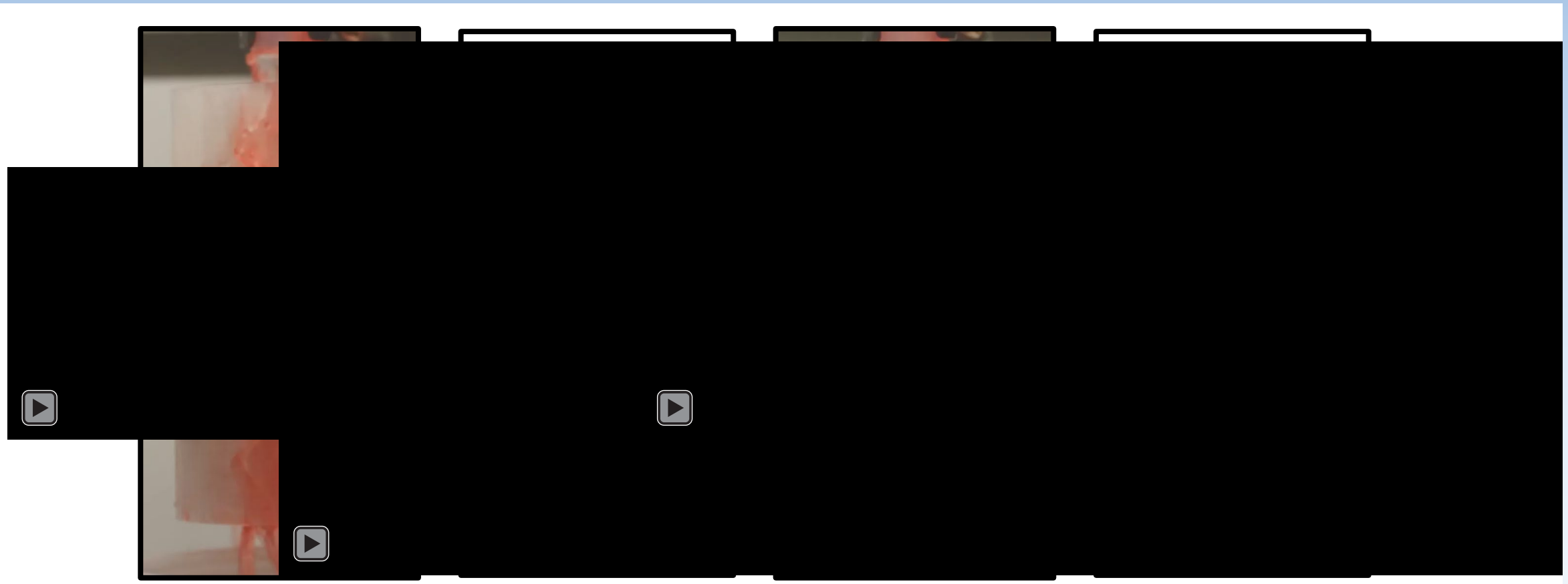
3D-printed materials for carbon capture





We apply our expertise in controlling mass transport to develop new carbon capture and CDR technologies

Performance carbon capture improvements through advanced manufacturing



250Y

Schwarz D

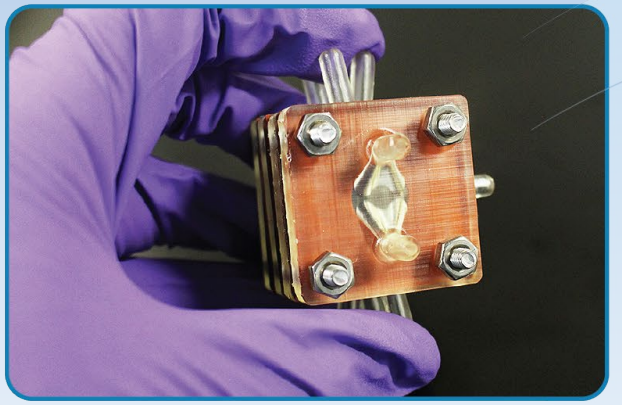
How can we make it matter?

2500 m^2

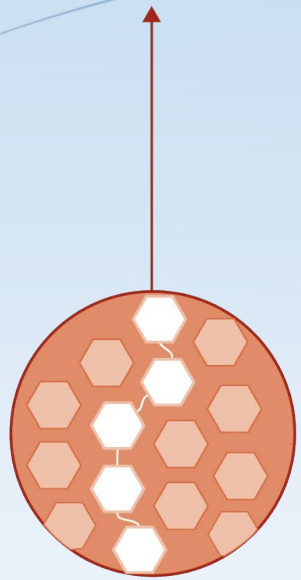
0.008 m^2

We are bridging gaps to increase rate of scale-up of climate technologies

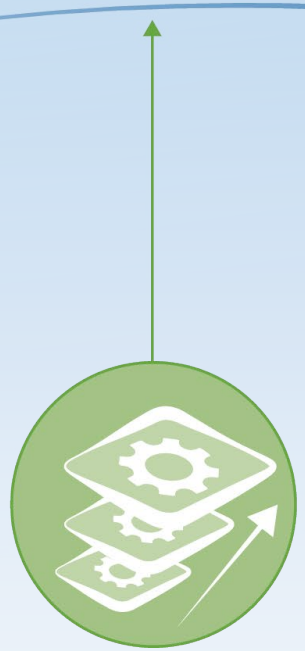
Informed by risk assessment
design-build-test cycle at increasing scales



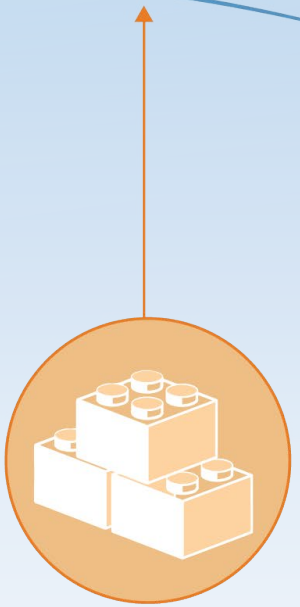
LAB-SCALE



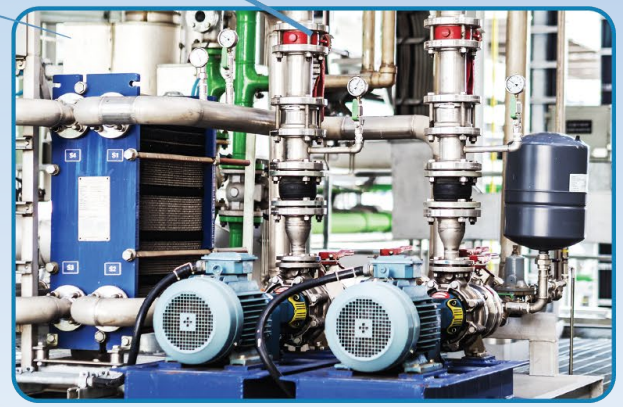
Identify critical path and risks



Predict scaling behavior and emergent phenomena



Retain performance in scaled, manufacturable units

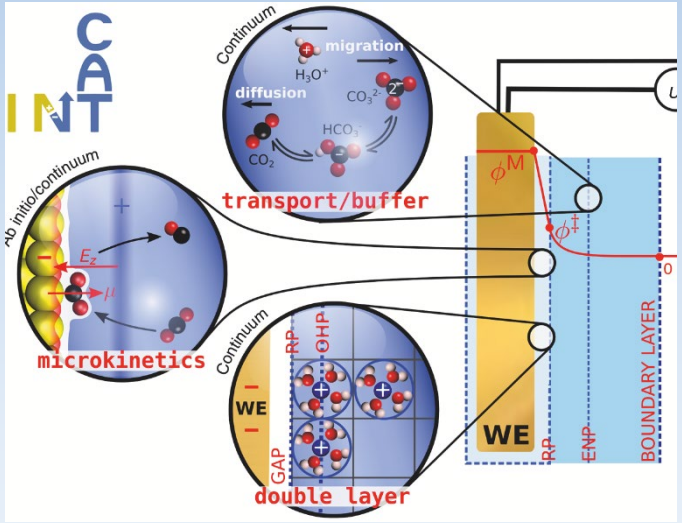


PILOT-SCALE

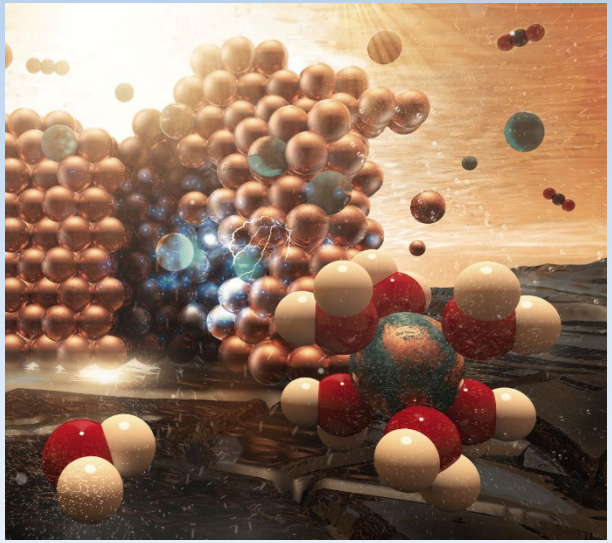
We are developing capabilities to address three major gaps to technology maturation at LLNL

Challenges in scaling CO_2 electrolysis

Multi-scale Complexity of Chemistry and Physics



Systems Degradation and Durability



Disruptive Technology Scale-up

Technology is disruptive and unproven.

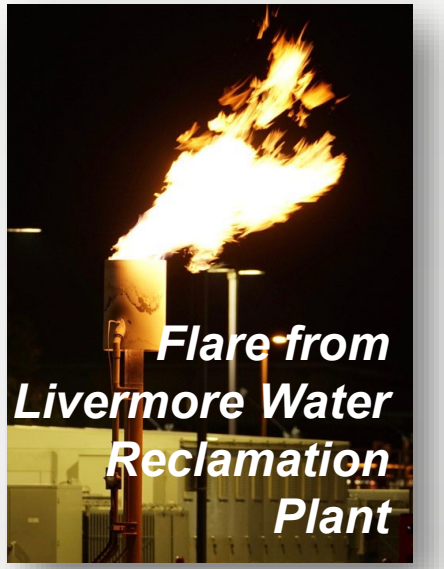
Who will be first movers to buy down investment risk? How can National Labs help?

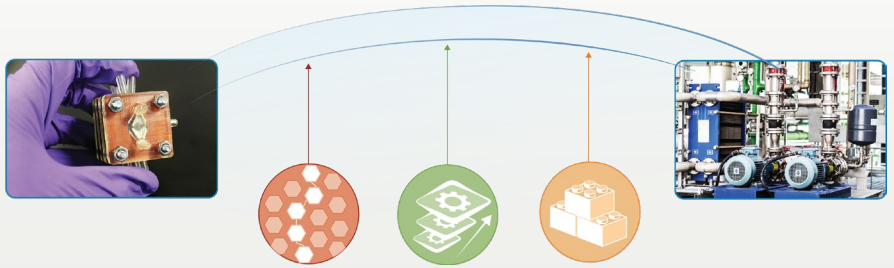
Accelerating CO_2 Conversion in the West

- Long term CO_2 electrolyzer demonstrations
- Partnerships between CO_2 product manufacturers and customers (and national labs can be the “glue)
- California carbon utilization demonstrations
- Prototyping Facilities

National Lab demonstration projects with California students will de-risk the technology and prepare the workforce

Demonstrating the benefit of carbon capture and utilization in California communities





Closing the gap between bench and pilot scale in climate technologies

National Labs can be a Major Resource for CO_2 Conversion Manufacturers and Customers.

THE LLNL CARBON INITIATIVE

The Livermore Valley Open Campus (LVOC)

Building and expanding collaborations with industry and academia

- 84,000 visitors and 7,700 events hosted since June 2011 opening
- B642: 22,000 ft^2, 104 offices, two conference rooms, large open collaboration spaces
- B643: 3,000 ft^2, large conference room, kitchen
- Next steps:
  - Prototyping, partnership, and bio buildings proposed
  - UCOP refurbishment of University of California Livermore Collaboration Center (UCLCC) ongoing