THE LLNL CARBON INITIATIVE

Biomass Carbon Removal and Storage (BiCRS) and Direct Air Capture (DAC): Impacts and Research Needs in California

EPIC Strategic Goals Emerging Strategies Workshop:

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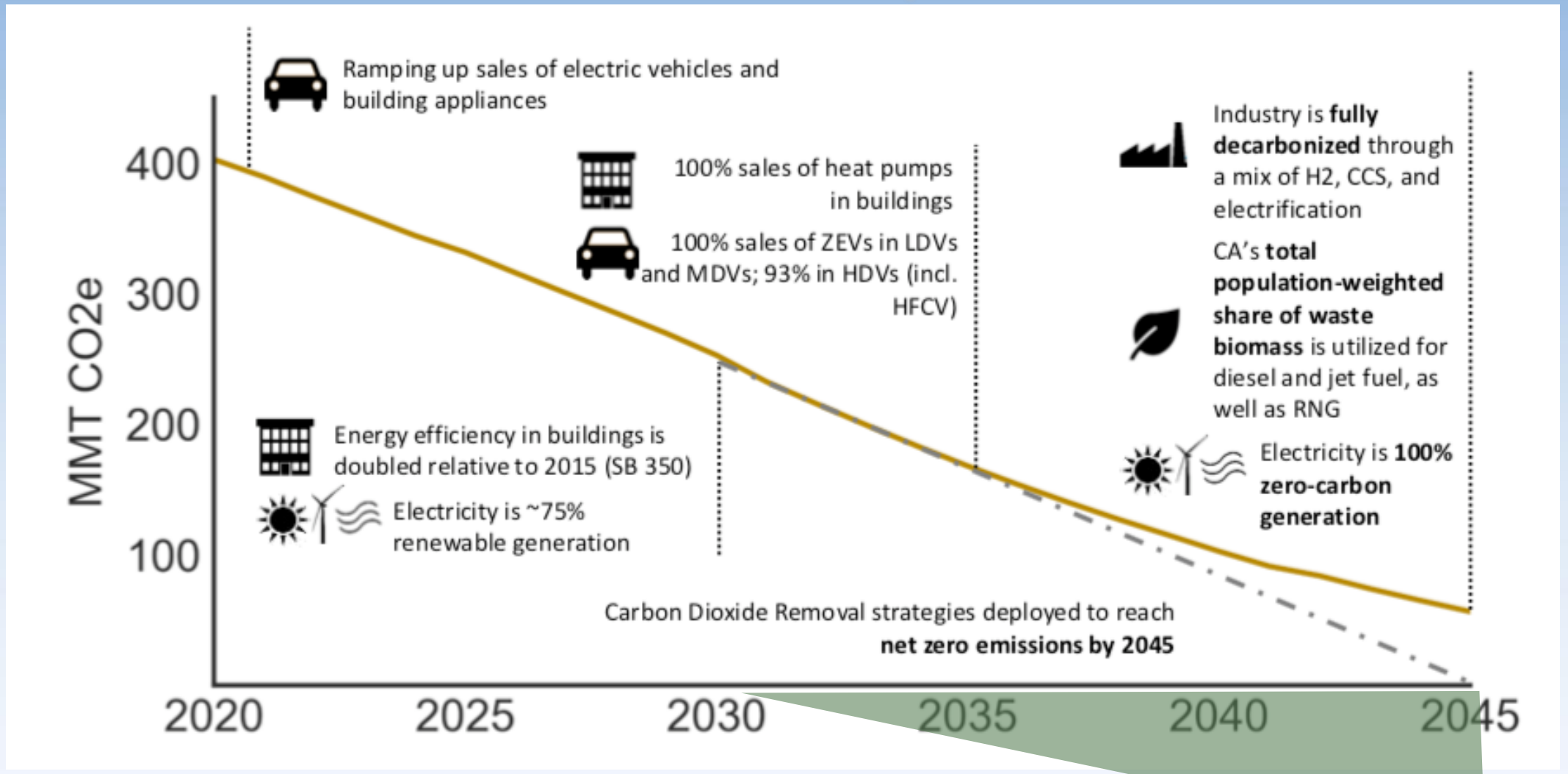
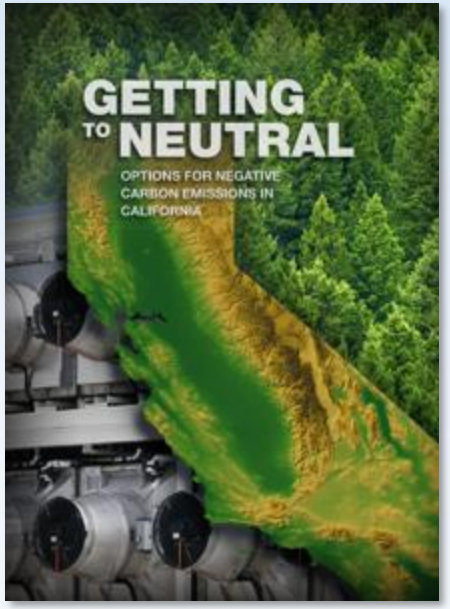
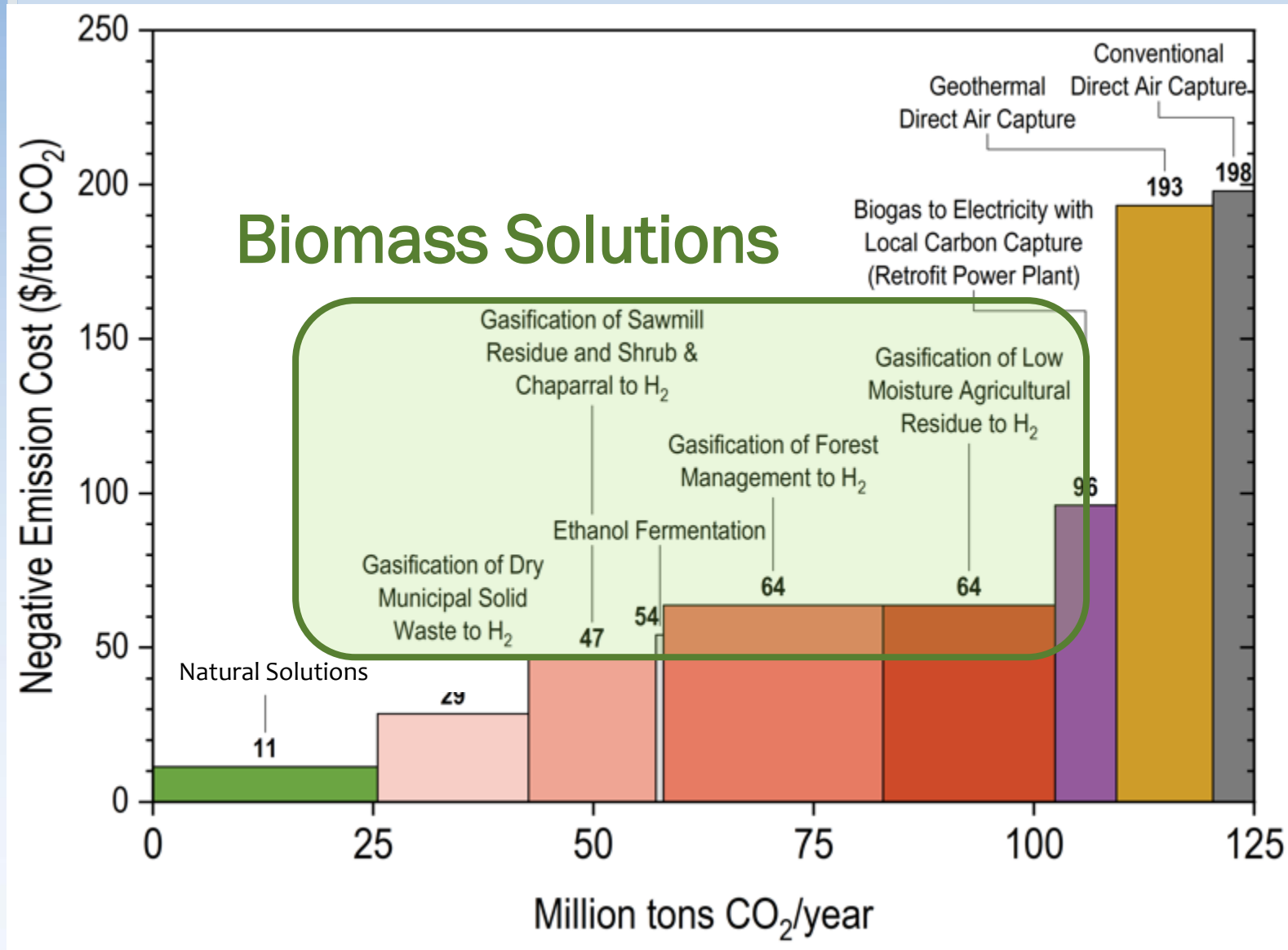
California's Path to Zero Requires Carbon Removal



LLNL estimated that 125 M tons/yr of negative emissions capacity would comfortably meet the need – especially if some measures are slow

California's least-cost path to 125 Mt/year of durable carbon removal averages ~$60/ton





Getting to Neutral Results: The lowest cost set of solutions for removing 125 million tons of CO_2

- Natural and Working Lands

25 MT/year

- BiCRS: Conversion of Waste to Fuels with CO_2 Storage

84 MT/year

- DAC: Direct Air Capture with CO_2 Storage

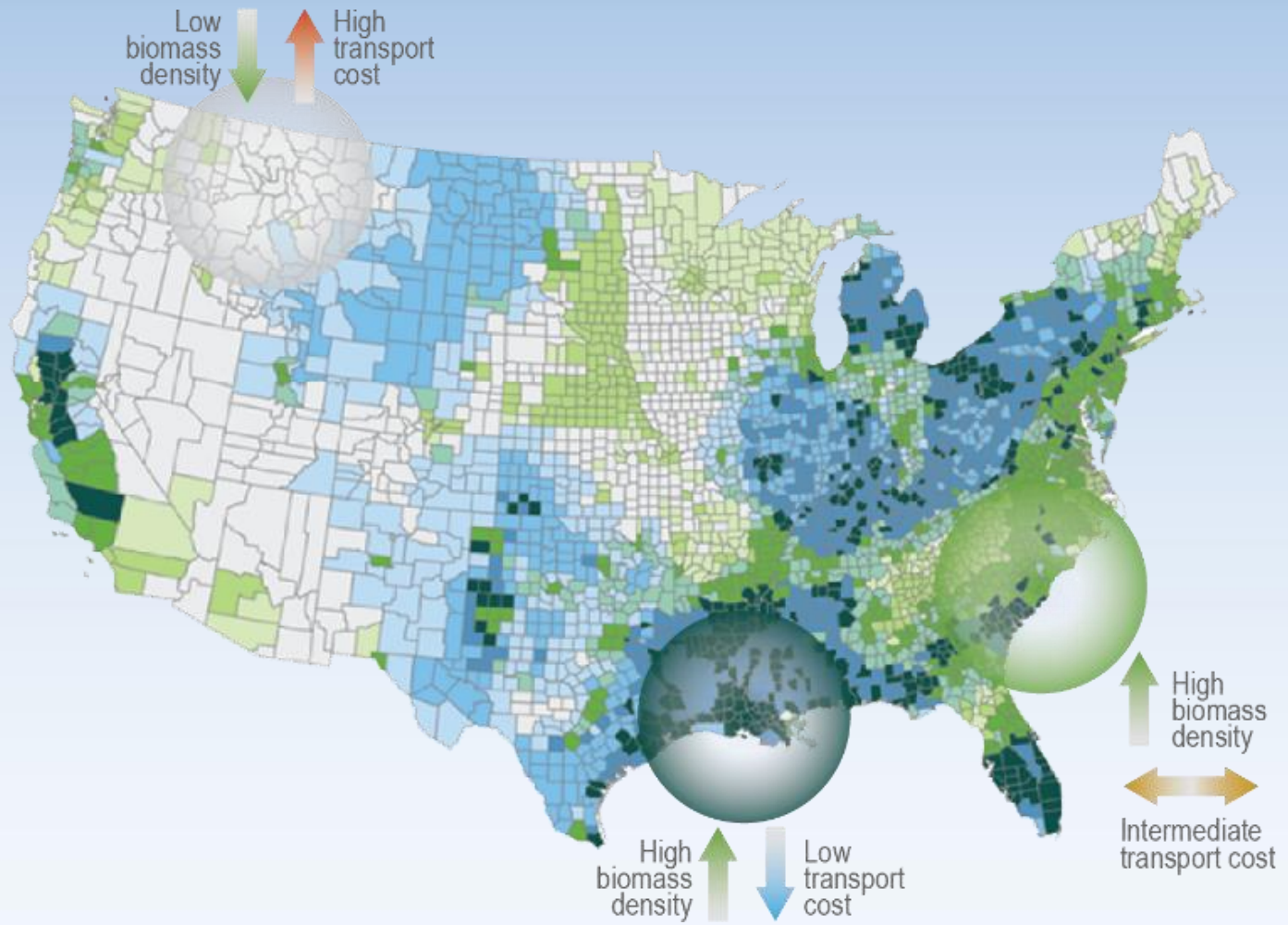
16 MT/year

Technological readiness: mid-to-high—with substantial co-benefits for CA, but significant implementation barriers remain for BiCRS and DAC

Biomass Carbon Removal and Storage

Put waste biomass to work to reach climate goals

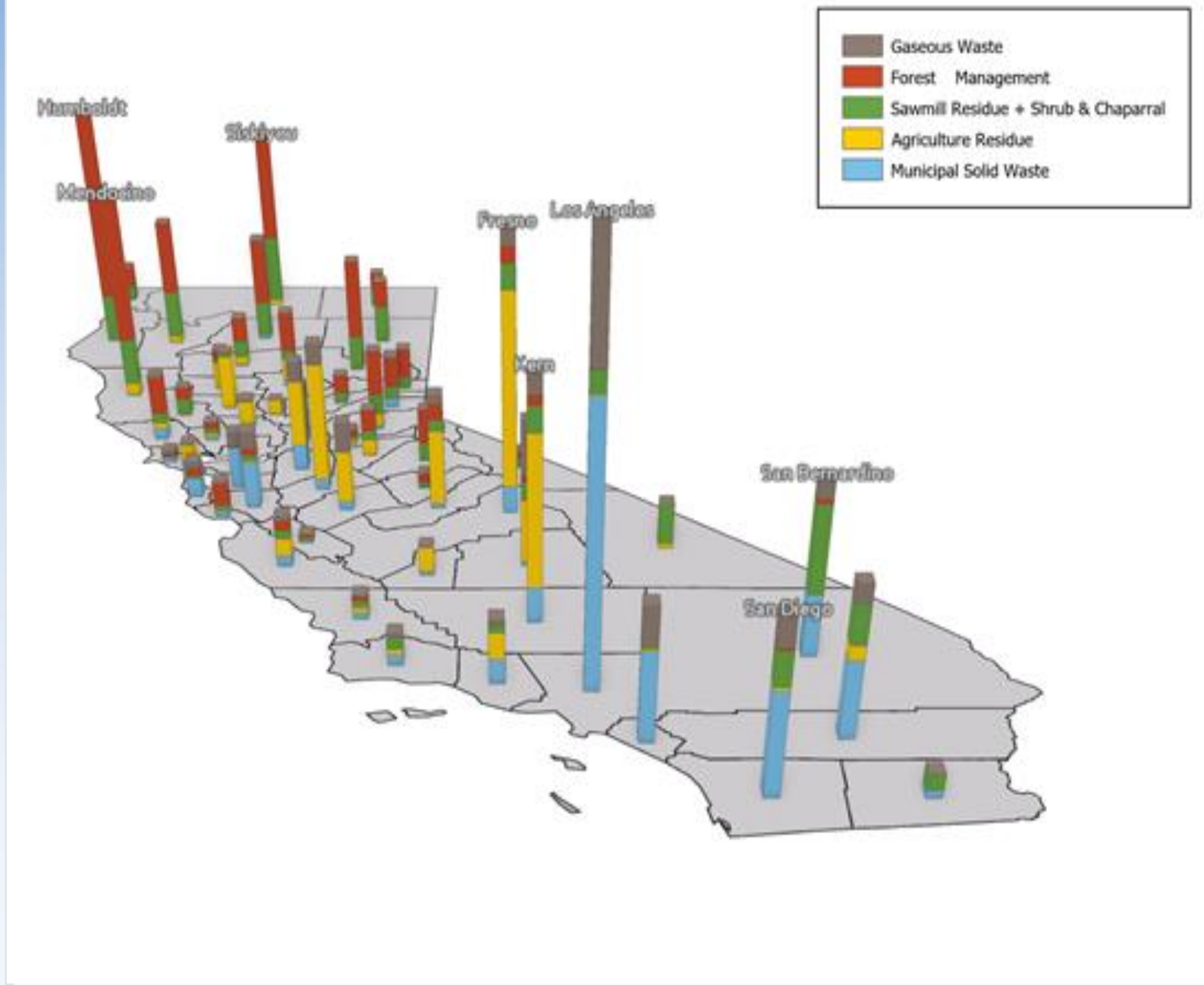
The regions of highest opportunity for BiCRS are located where there is abundant waste biomass and local geologic carbon storage



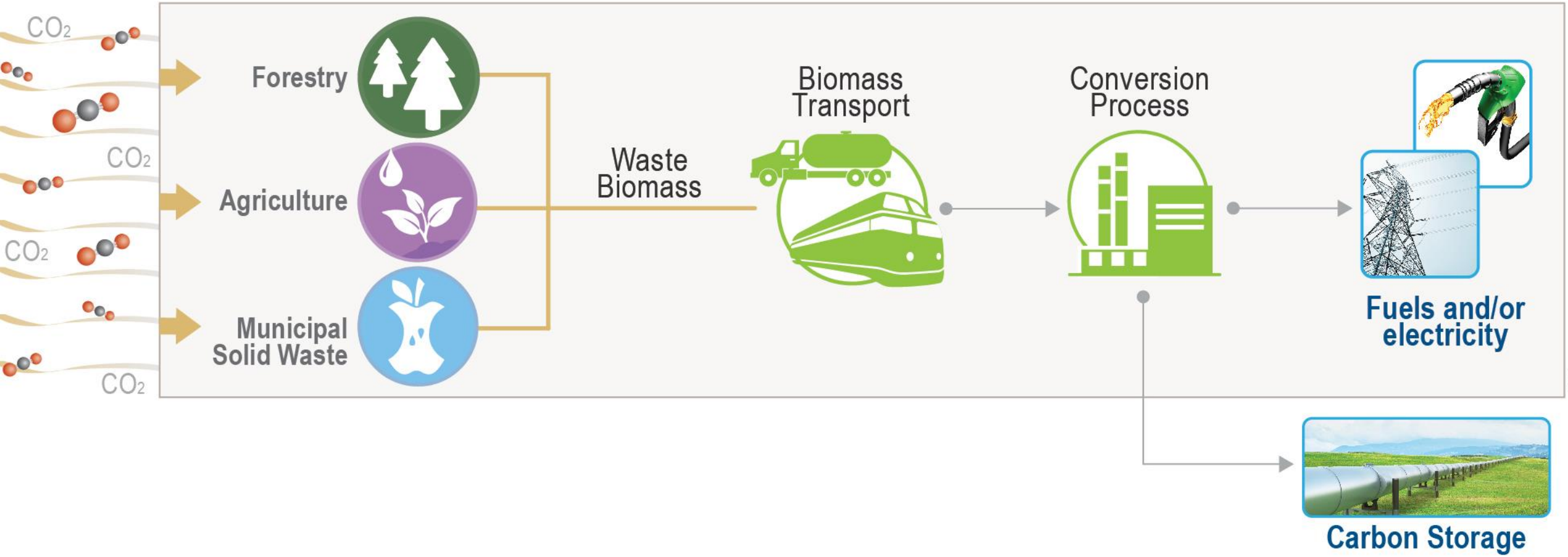
B. Mordick Schmidt, et al. "Carbon Negative by 2030: CO_2 Removal Options for an Early Corporate Buyer" 2022, LLNL-TR-832071.

What does it take to obtain climate/ environmental benefits from CA's 58 million tons of waste biomass?

- Supply chain
- Gasification
- Manage CO_2 from digesters



BiCRS: Supply Chain and Logistics Pose the Greatest Barriers
Sourcing, siting, and offtake



Gasification of Waste Biomass to Hydrogen:

- highest carbon removal capacity
- lowest cost per ton CO_2
- while reaching state's hydrogen goals

Fulcrum Bioenergy Gasification Facility

Gasification to Hydrogen Barriers to Implementation

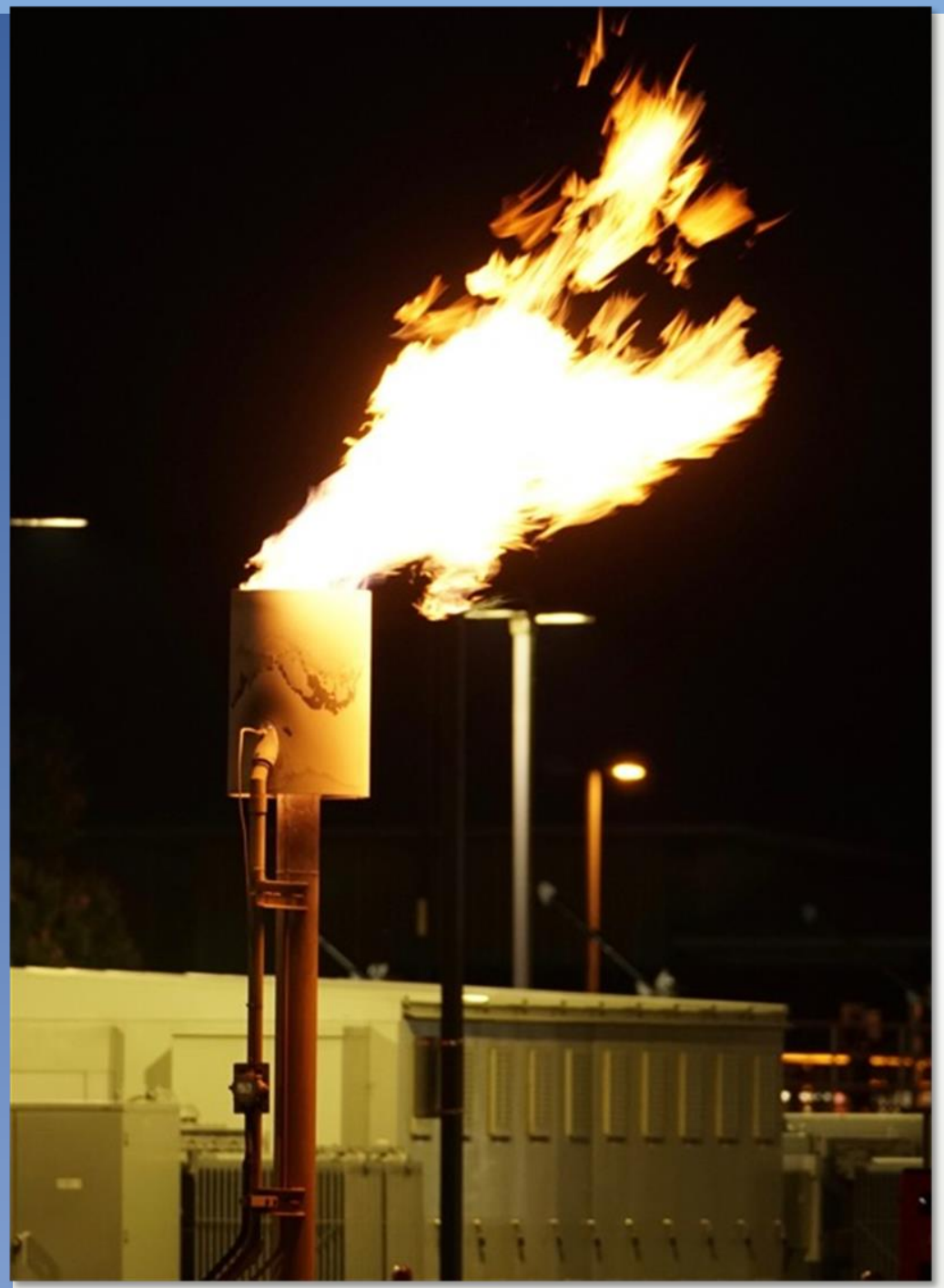
Sourcing stable long term supply of biomass – Unique challenges for forest, agriculture, and municipal waste biomass

High capital cost of facilities to realize economies of scale means high investment risk

Technology is proven, but feedstock variability and unique biomass attributes pose technical risk

Capture of Biogas CO_2 from Dairies, Landfills, and Wastewater Treatment:

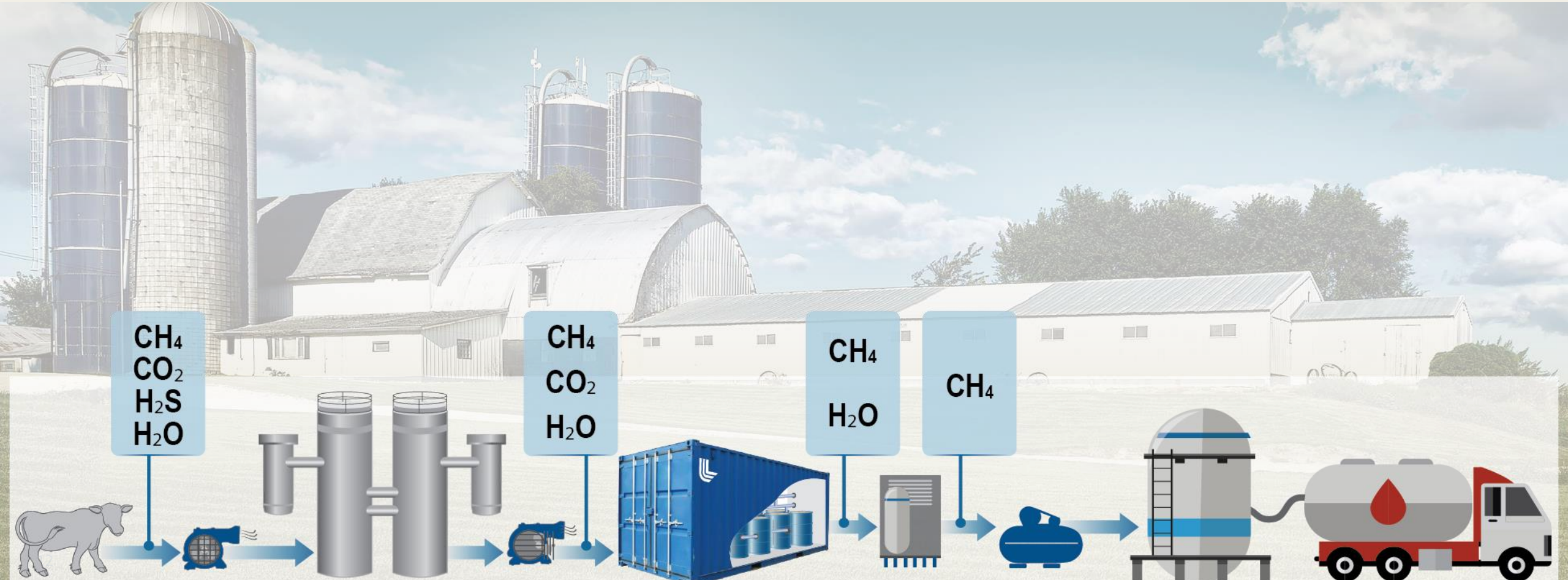
- biomass already collected
- conversion technology exists
- generate lower CI renewable natural gas
- avoid flaring



Flare from Livermore Water Reclamation Plant

Biogas CO_2 Capture: Barriers to Implementation

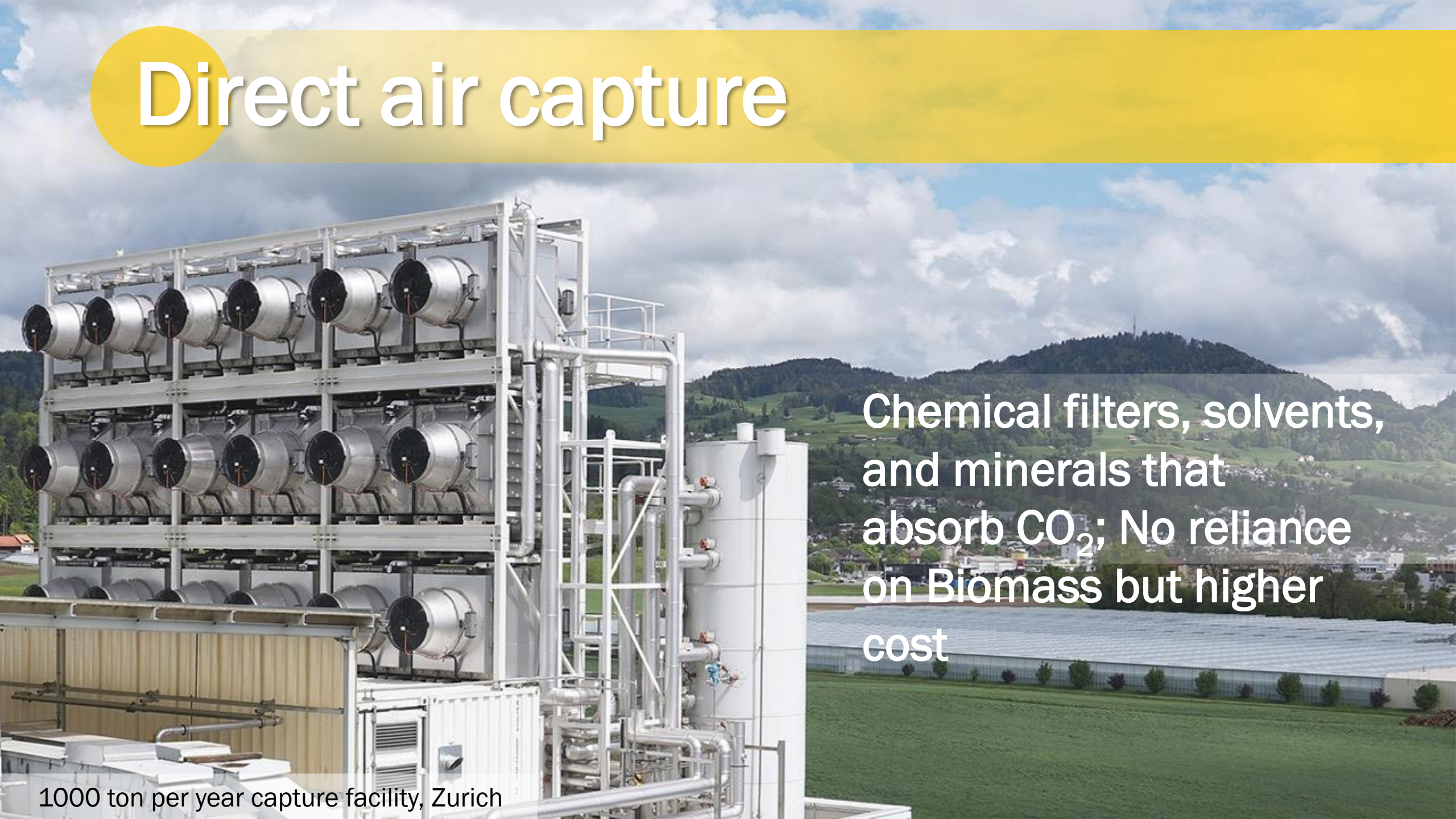
- small scale distributed CO_2 sources
- lack of economical small scale CO_2 capture technologies



BiCRS Analysis Needs

- Deployment rate-what is needed to reach California goals?
- Understanding of highest impact investments to buy down costs
- Needed incentives/risk reduction along the supply chain to catalyze the industry (costs vs. revenue today)

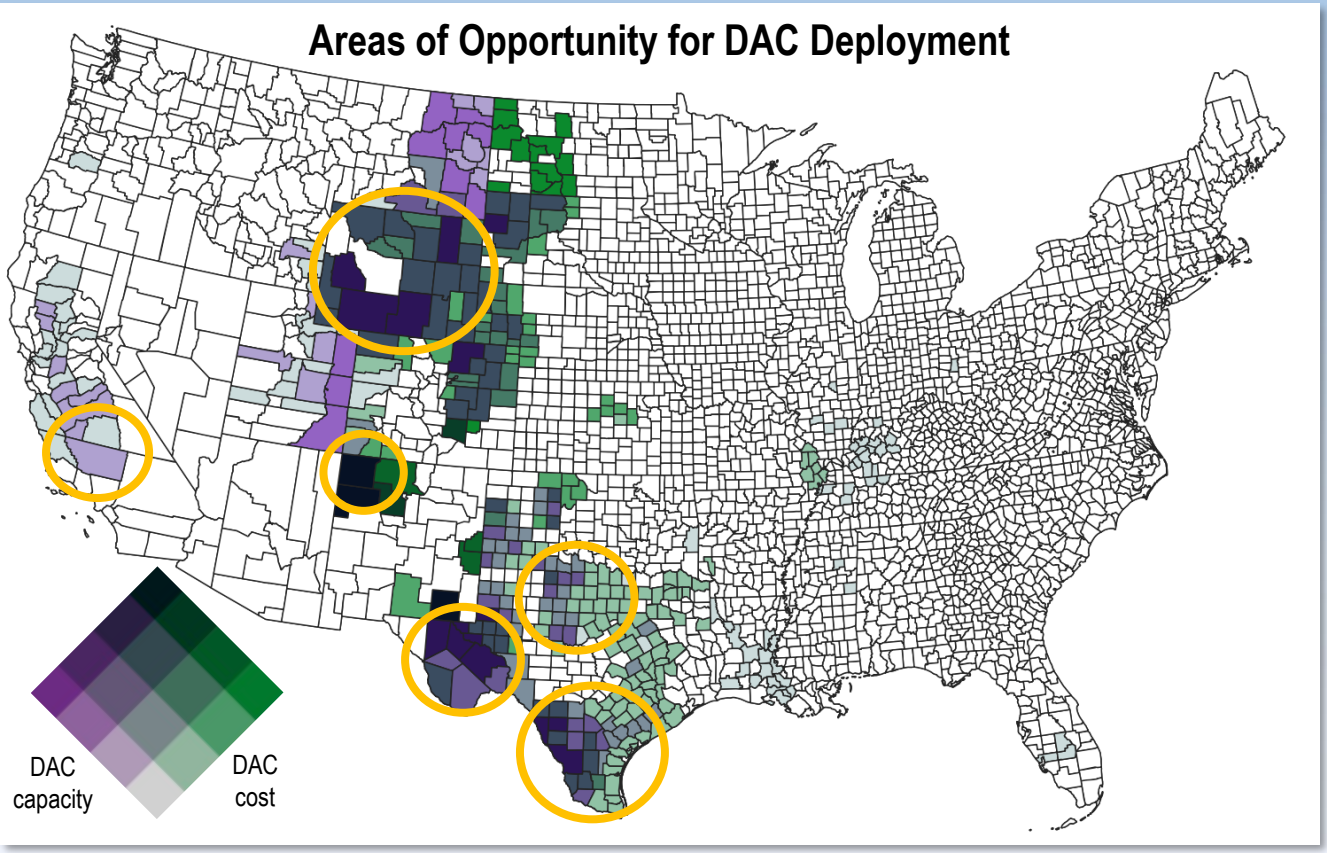
Direct air capture

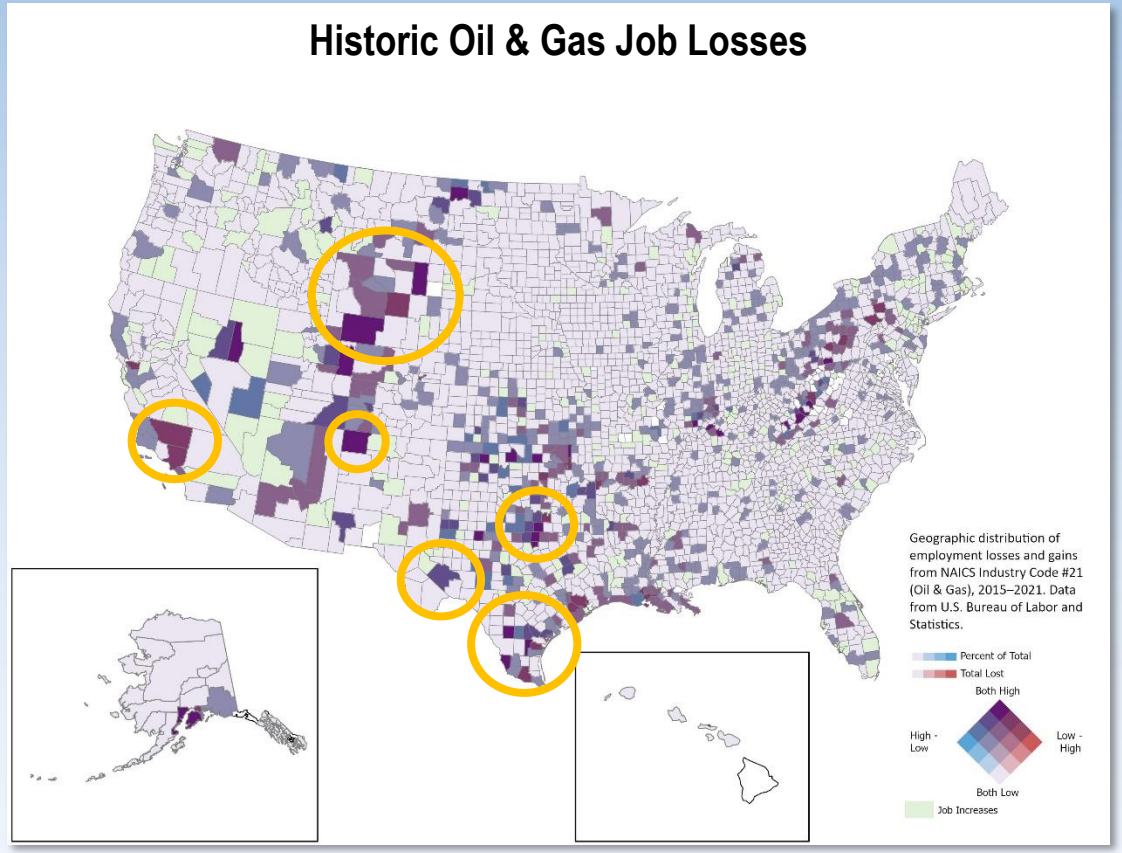


Chemical filters, solvents, and minerals that absorb CO_2; No reliance on Biomass but higher cost

1000 ton per year capture facility, Zurich

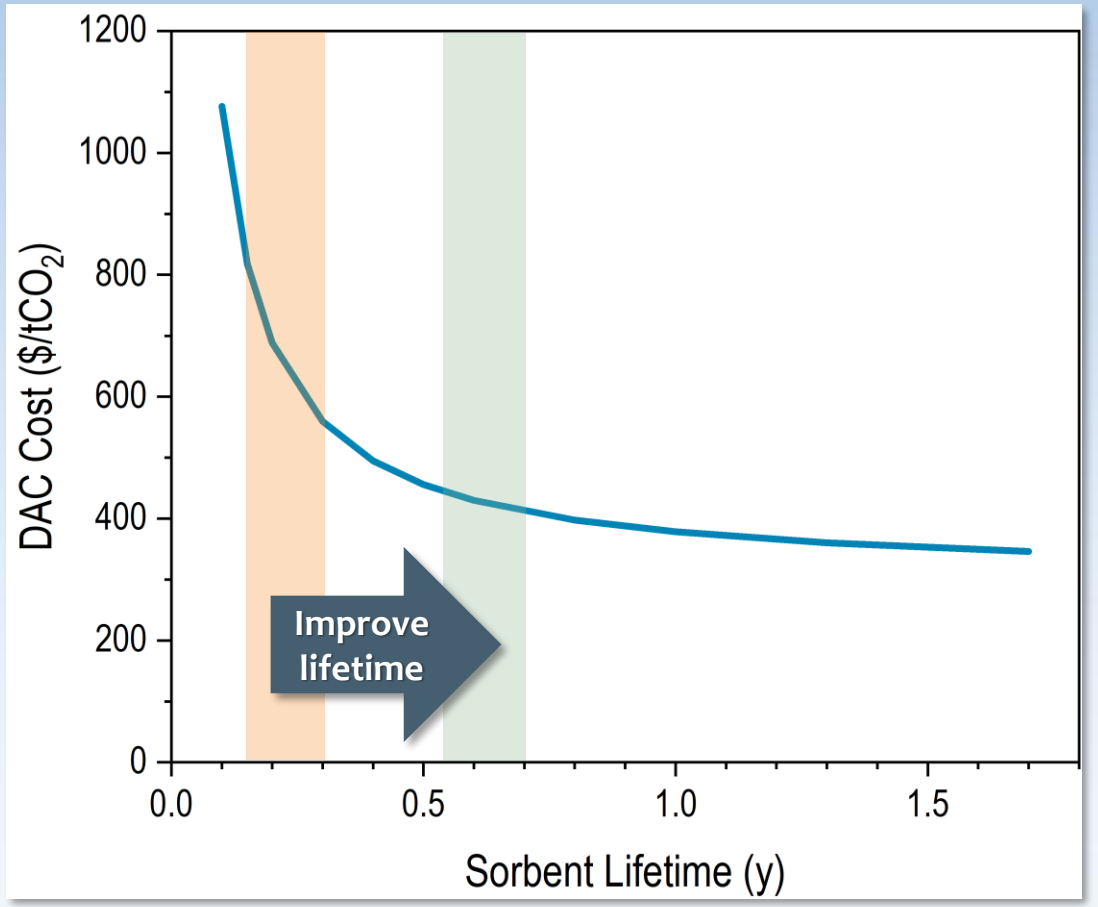
California is an area of opportunity for DAC

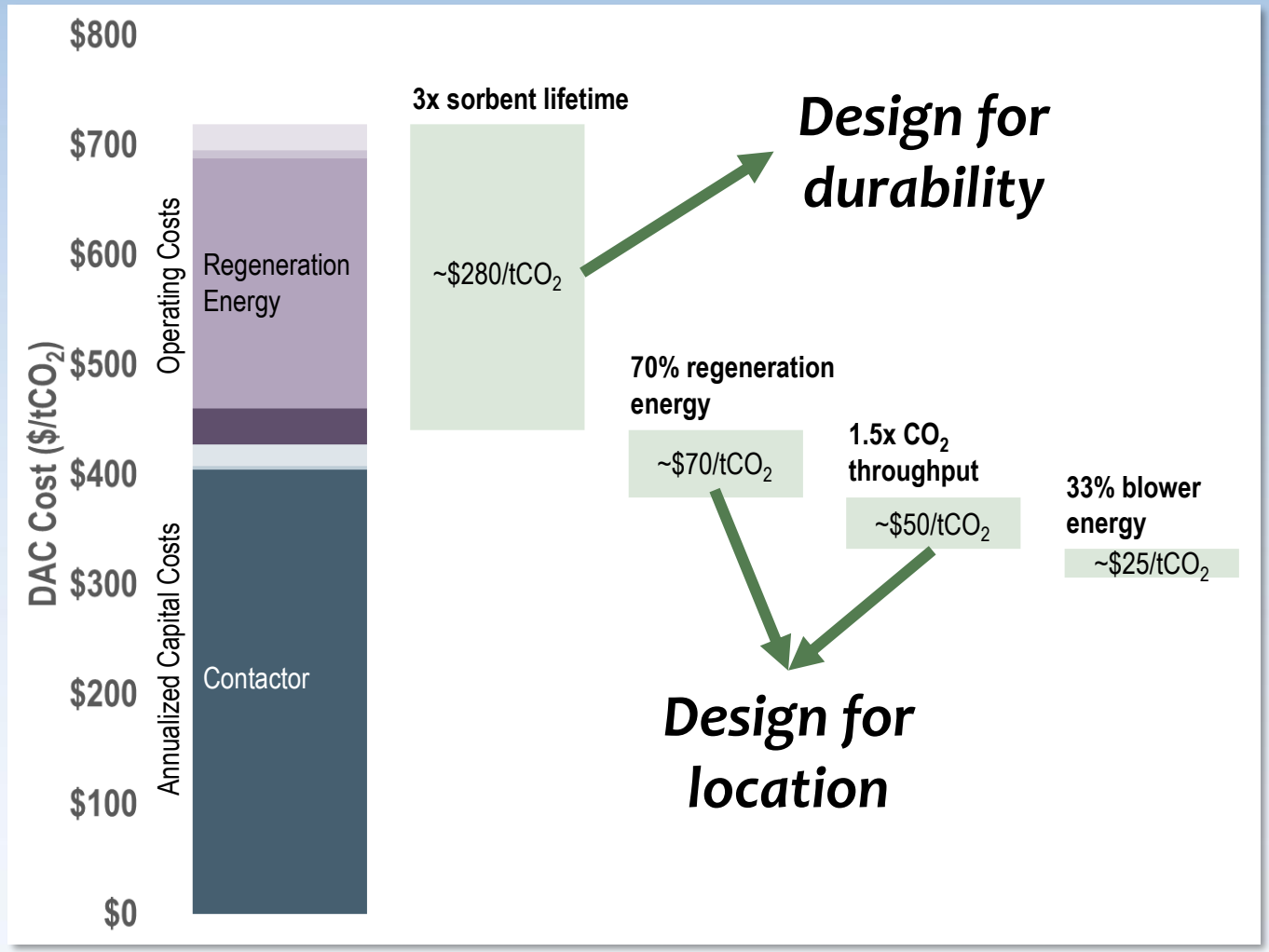




How do we design materials tailored for California's central valley (temperature, humidity)?
Can we co-optimize materials, structures, and processes to maximize throughput with minimal energy?

Results from system- and process-level analysis: improved sorbent durability and design for local and seasonal conditions are needed





In two years carbon removal has boomed

amazon

250,000 metric tons of carbon removal over 10 years from STRATOS, 1PointFive's first DAC plant

Ørsted's Avedøre Power Station in the Greater Copenhagen area. Credit: Ørsted.

Ørsted launches landmark CCS project in Denmark

Microsoft has agreed to purchase 2.76 million tonnes of carbon removal over 11 years from the project, representing one of the world's largest carbon removal offtake agreements to date.

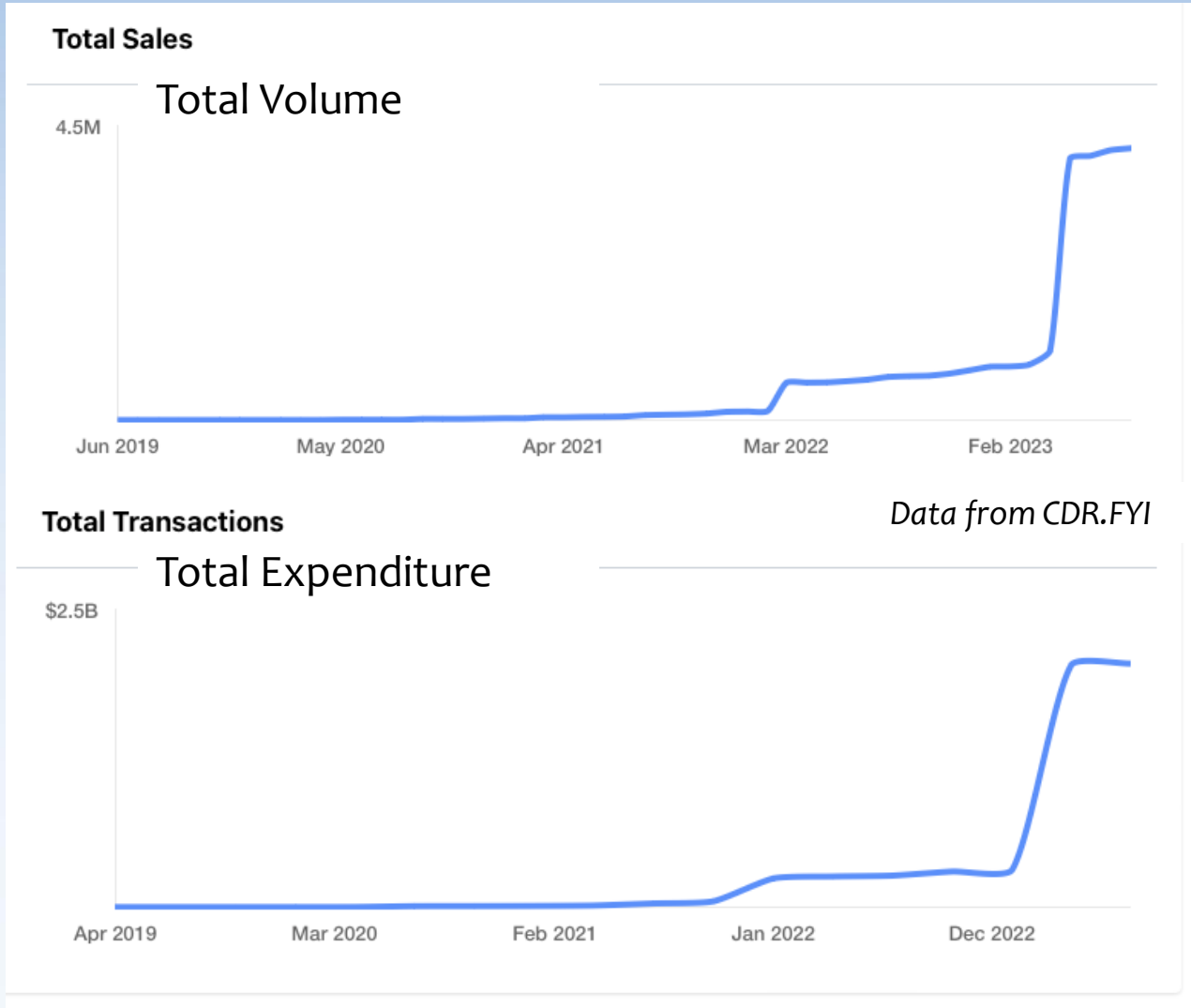
Microsoft has inked one of the largest carbon dioxide removal (CDR) deals to date with Direct Air Capture (DAC) startup Heirloom, which involves 315,000 metric tons of carbon removal estimated to be worth $200 million.

Boston Consulting Group's *medium scenario* yields a global demand of ~70–230 Mt CO2 p.a. in 2030–2040, with a market size of ~$15 billion–$45 billion. The average voluntary durable CDR portfolio price is assumed at ~$250/t CO2 in 2030 and ~$200/t CO2 in 2040. North America's share would be roughly 36% of that market.

https://web-assets.bcg.com/44/75/58c3126c4050b74ae75b037e9434/bcg-the-time-for-carbon-removal-has-come-sep-2023.pdf

BCG

Commercial CDR is strongly capacity limited today: the market is paying high prices

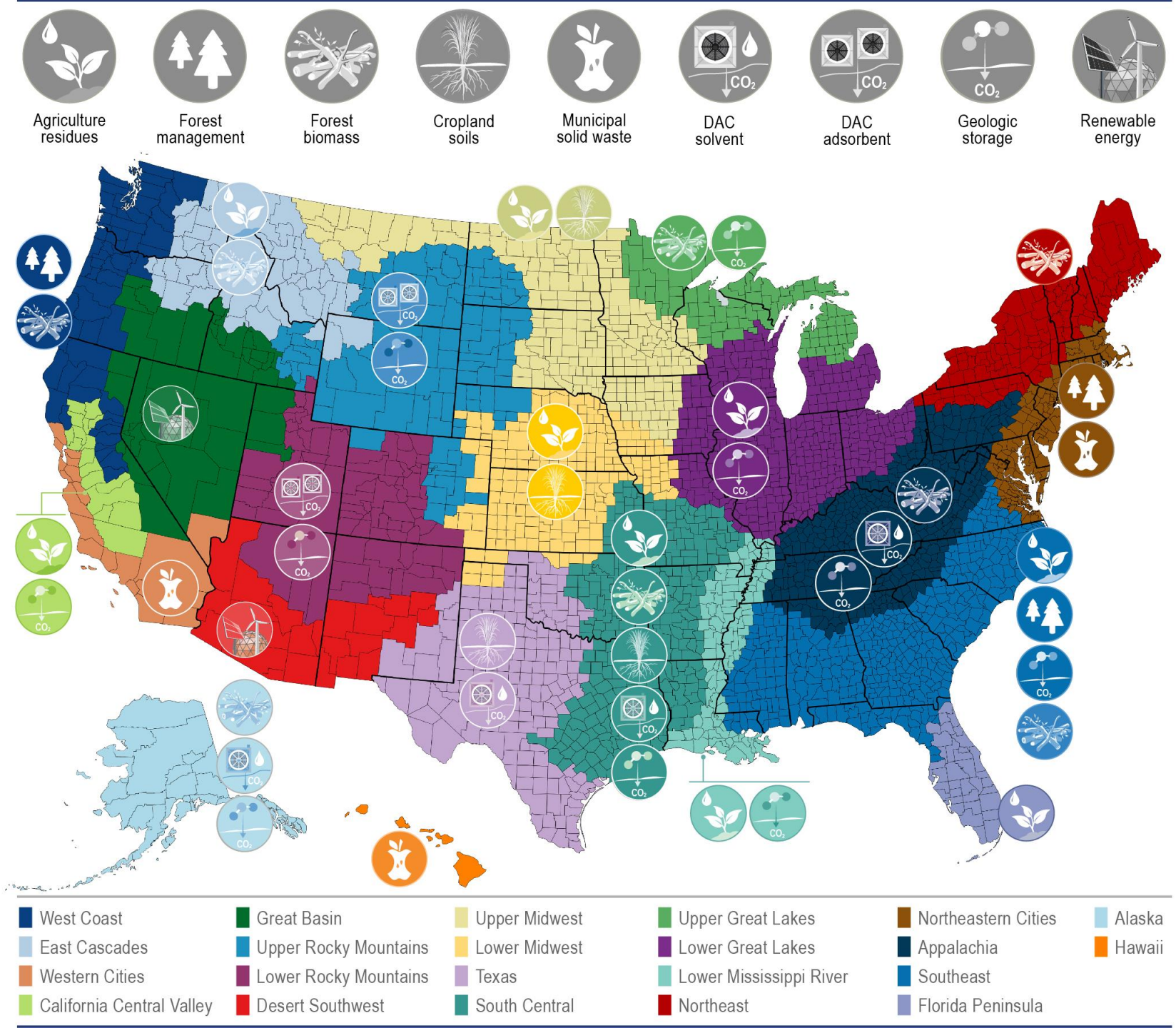


Data from CDR.FYI

Costs vary from $1200/ton (ocean electrochemical) to $112 (biomass)

Overall average about $550/ton

California is Poised to Lead the Nation in Carbon Dioxide Removal



The Getting to Neutral big carbon tent

Our goal is to understand options, connect and inspire players (business, government, community) who want to play a role in carbon removal

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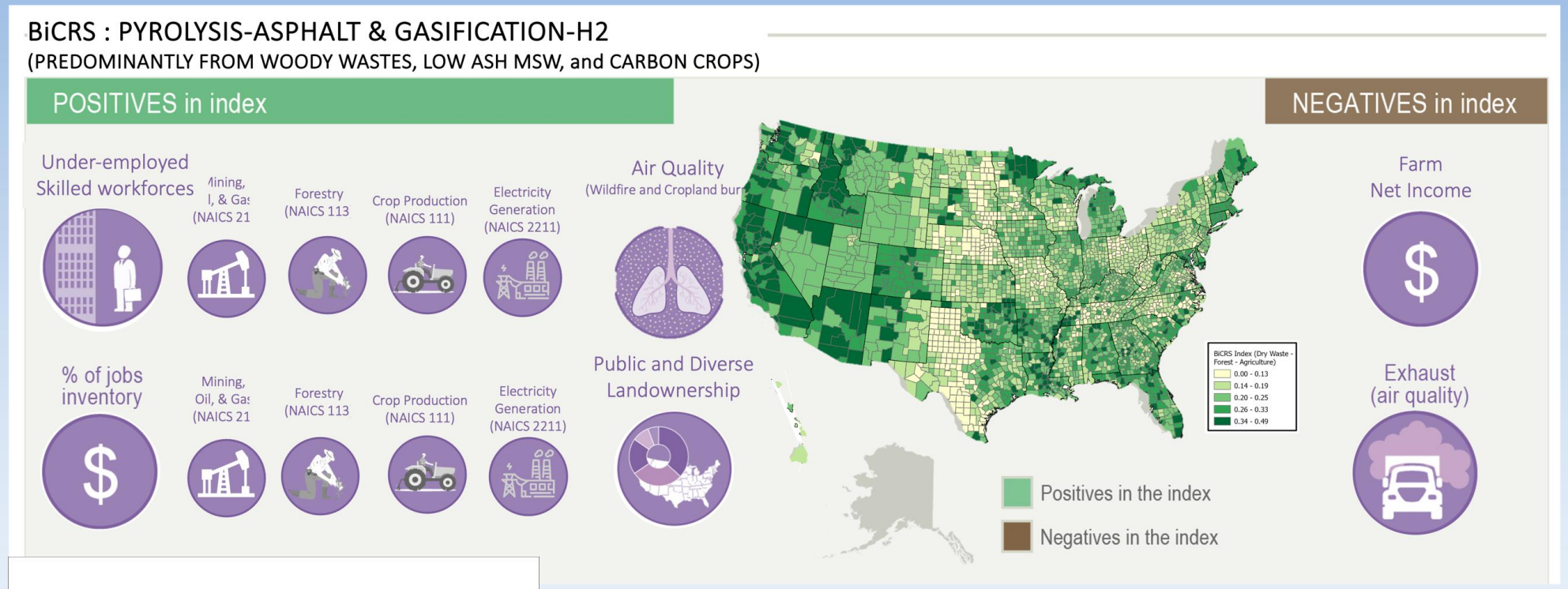
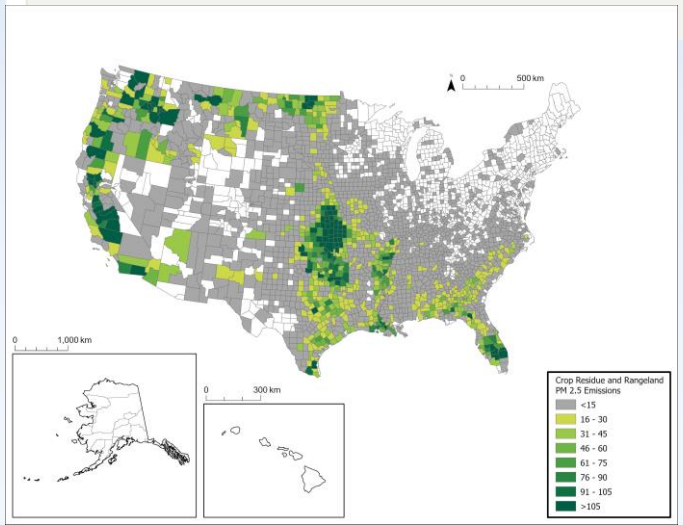
EEEJ Considerations





Getting to Neutral Big Ideas:

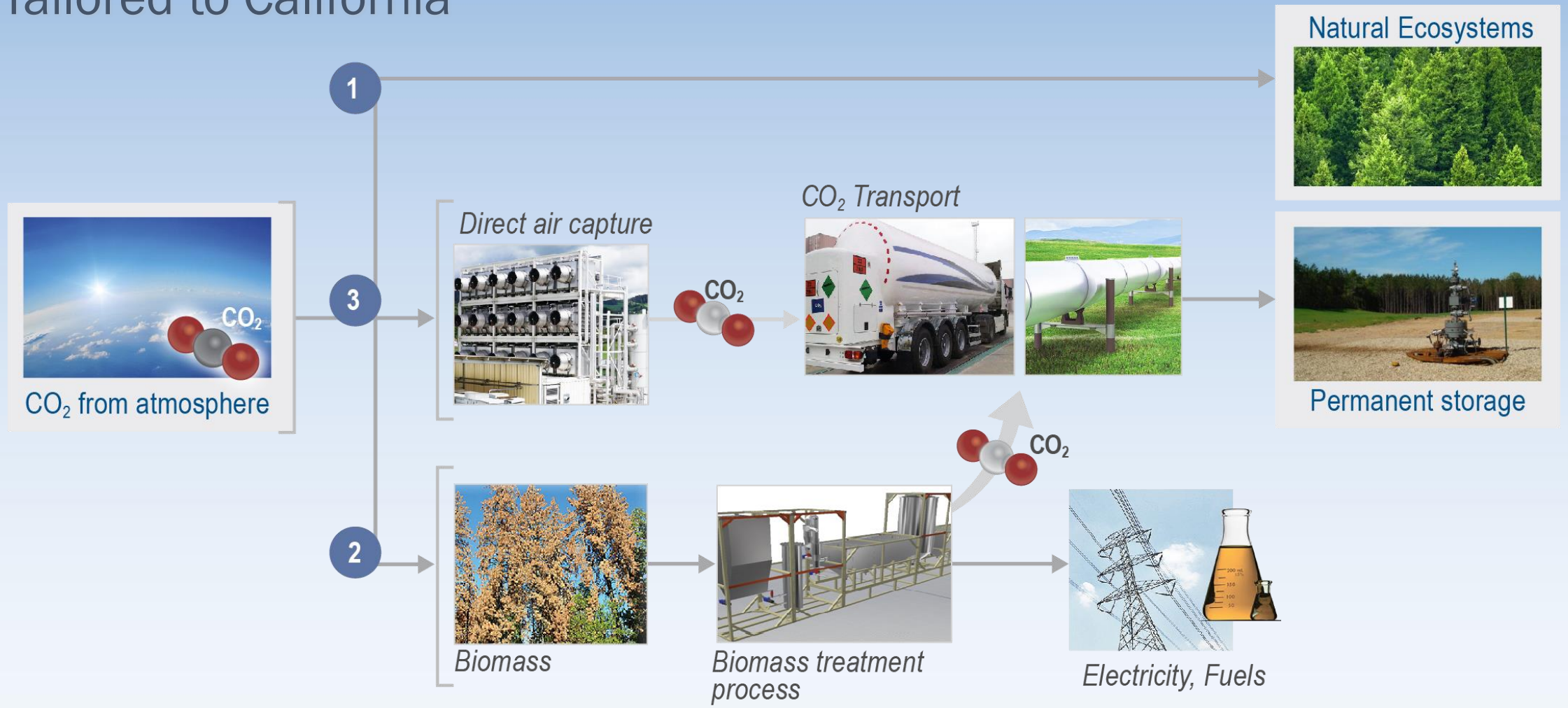
1. Mother nature can't do it on her own
   - *Key outcome for State Legislators*
2. Waste biomass should be used to draw down CO_2 first, rather than emphasize energy
3. H_2 from waste biomass gasification with CO_2 storage is a leading technology for California

8rivers

Fulcrum

Red Rock Biofuels

Robust Solutions Tailored to California



General BiCRS Knowledge and Implementation Gaps

Logistics/Adoption

- Supply chain (Biomass)
- Co-location and multi-stakeholder challenge

Analysis

- Deployment rate-what is needed to reach California goals?
- Understanding of highest impact investments to buy down costs
- Needed incentives/risk reduction along the supply chain to catalyze the industry (costs vs. revenue today)

Technical

- Integration of CO_2 capture with scale of biorefinery
- Biomass feedstock variability