Carbon Dioxide Removal – An Idea Whose Time Is Coming

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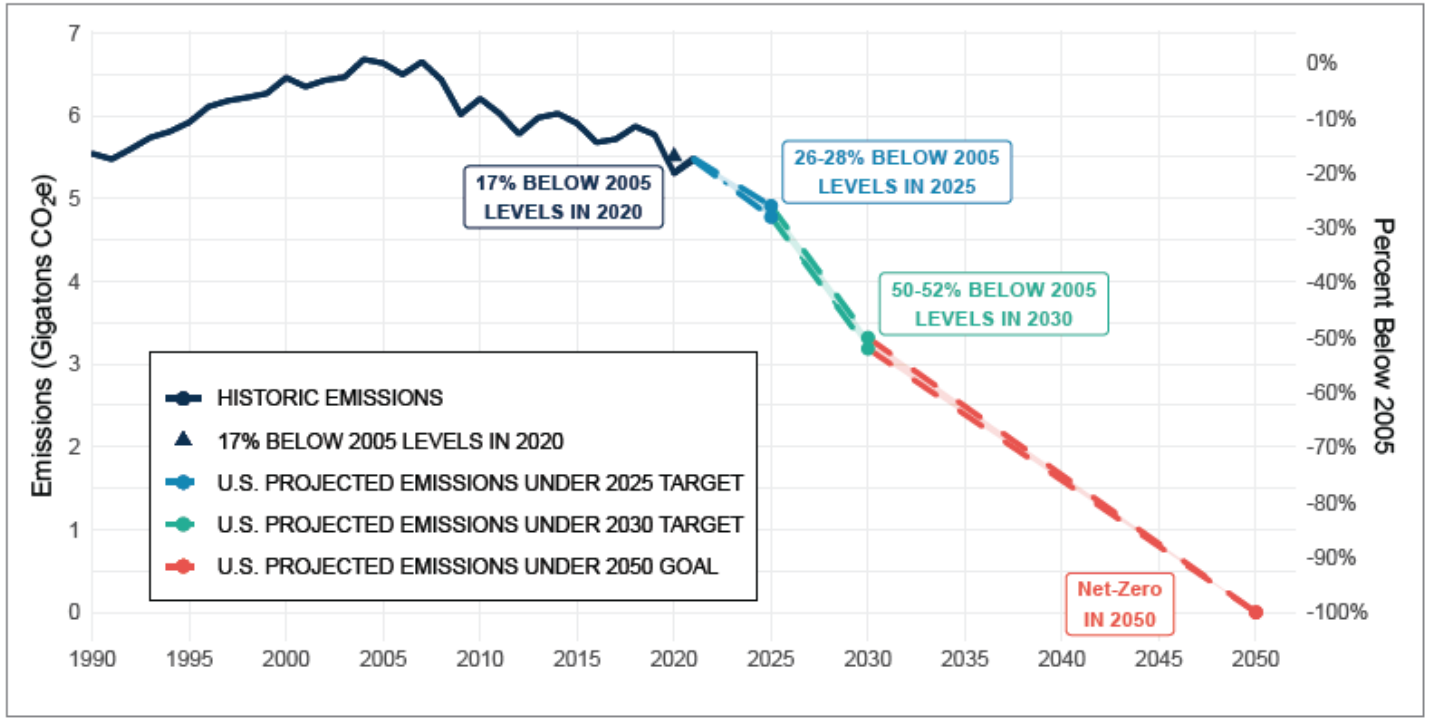
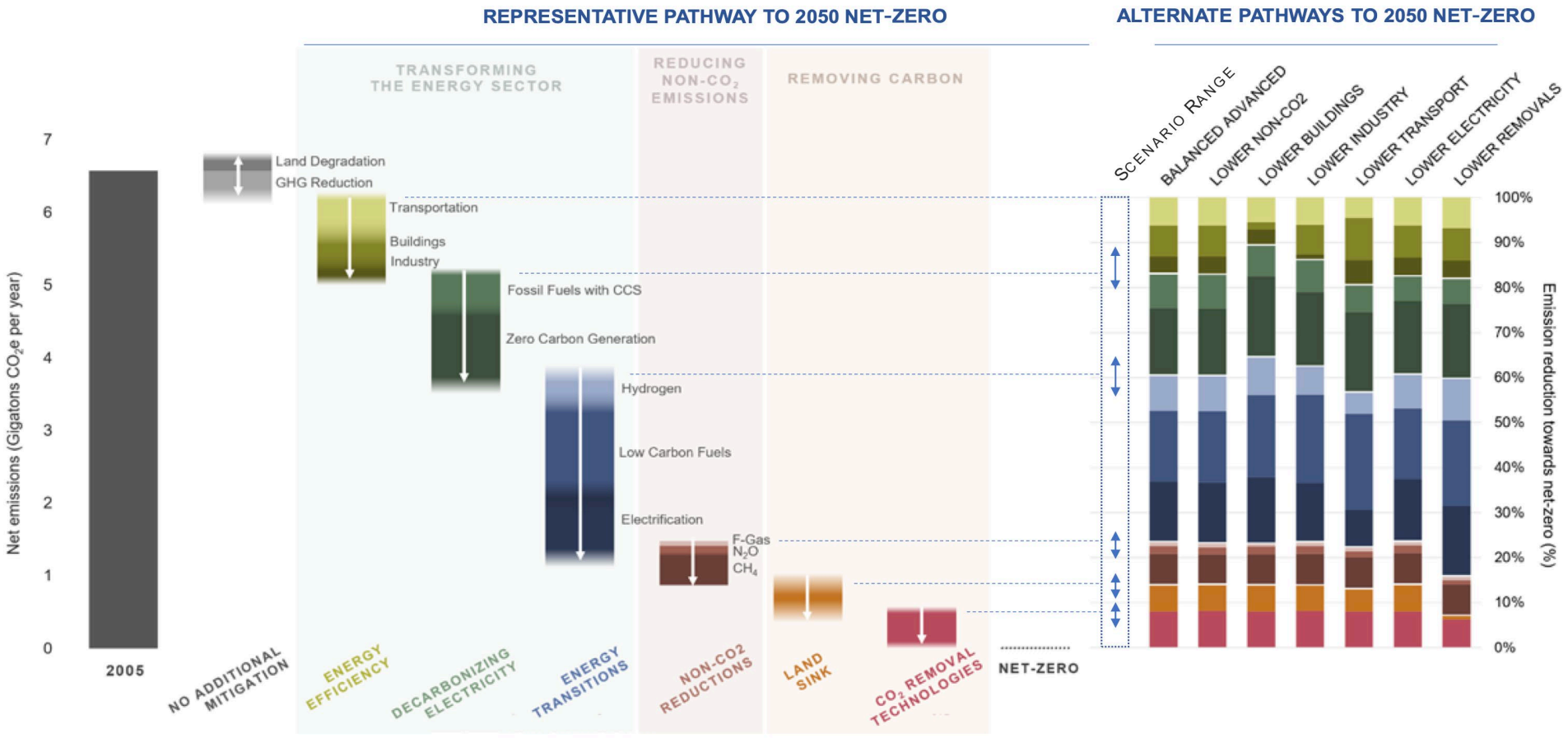

Emissions (Gigatons CO_2e)
Percent Below 2005
17% BELOW 2005 LEVELS IN 2020
26-28% BELOW 2005 LEVELS IN 2025
50-52% BELOW 2005 LEVELS IN 2030
Net-Zero IN 2050
HISTORIC EMISSIONS
17% BELOW 2005 LEVELS IN 2020
U.S. PROJECTED EMISSIONS UNDER 2025 TARGET
U.S. PROJECTED EMISSIONS UNDER 2030 TARGET
U.S. PROJECTED EMISSIONS UNDER 2050 GOAL
0
1
2
3
4
5
6
7
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
-90%
-100%
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050

THE LONG-TERM STRATEGY OF THE UNITED STATES
Pathways to Net-Zero Greenhouse Gas Emissions by 2050
NOVEMBER 2021

Net-zero by 2050: How Do We Get There (Or Close)?

For every complex problem there is an answer that is clear, simple, and wrong – H. L. Mencken



From *The Long-Term Strategy of the United States*

How Should I Think About Gigatons?

- 1 Gt = 1 billion tons
- US GHG emission = 5 Gt CO_2-equiv/yr

  = mass of ~11 gallons of milk each day for each person

- US plastics production = 0.06 Gt/yr
- US all petroleum products = 1 Gt/yr

How Fast Can Energy Transitions Occur?

Nuclear energy in US

- First US commercial nuclear power- 1957
- By 1975, 9% of electricity in US from nuclear power
- By 1995, 20% of electricity in US from nuclear power

Fuel ethanol in US

- 1985 – 600 million gallons
- 1995 – 1400 million gallons
- 2005 – 3900 million gallons
- 2015 – 14,000 million gallons

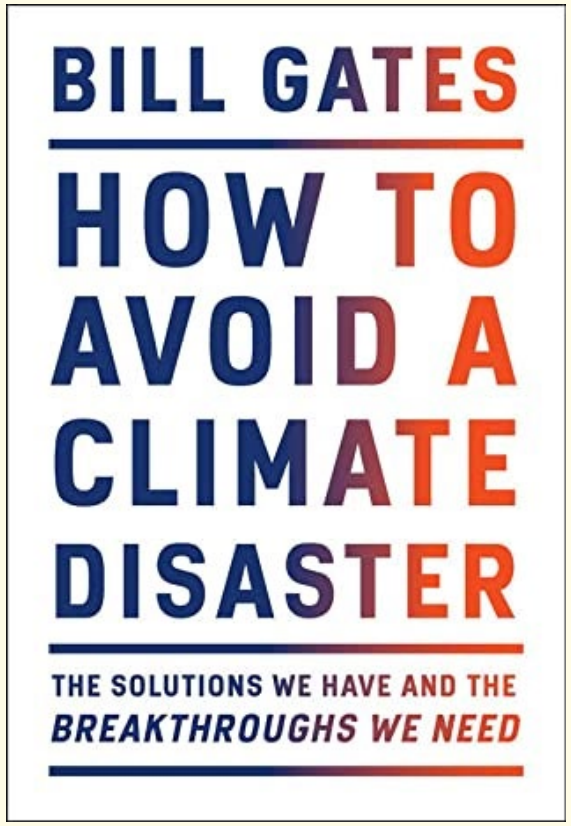
2035 is 1.1 decades from now

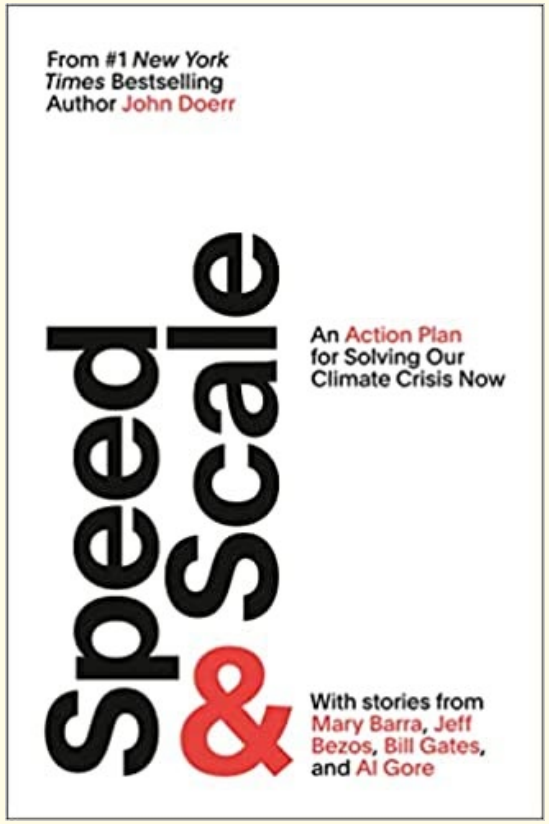
2050 is 2.6 decades from now

Net-zero by 2050: Can We Get There?

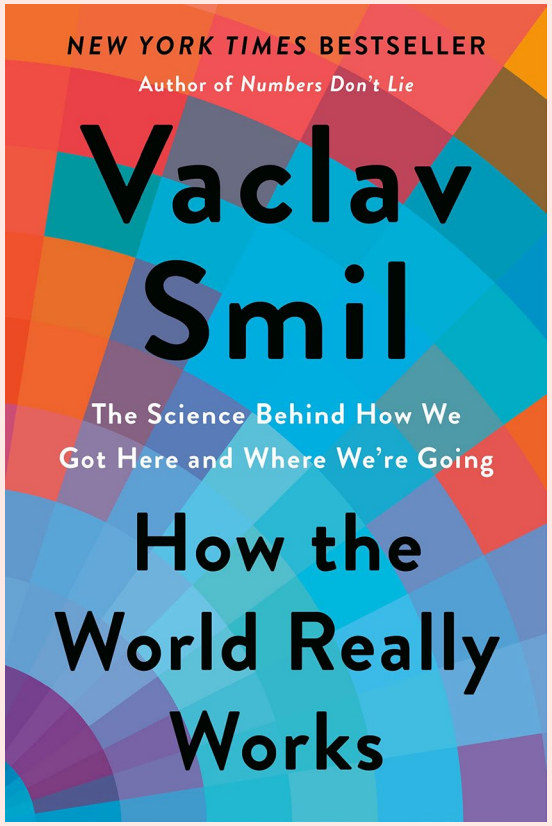
2050 is 2.6 decades from now

Yes





Maybe



Four Stages of Accepting Scientific Ideas

Attributed to J. B. S. Haldane

1. This is worthless nonsense
2. This is an interesting but perverse point of view
3. This is true, but quite unimportant
4. I have always said so

Carbon dioxide removal (CDR)

CDR = Remove CO_2 from the atmosphere (or ocean) *and* durably store it

CDR Primer Ch. 2 (cdrprimer.org): Editors Jennifer Wilcox, Ben Kolosz, Jeremy Freeman

1. Direct Air Capture (DAC)
2. Bioenergy with CCS (BECCS)
3. Biomass Storage
4. Soil Carbon Sequestration
5. Ocean Alkalinity Adjustment
6. Mineralization
7. Hybrid Concepts

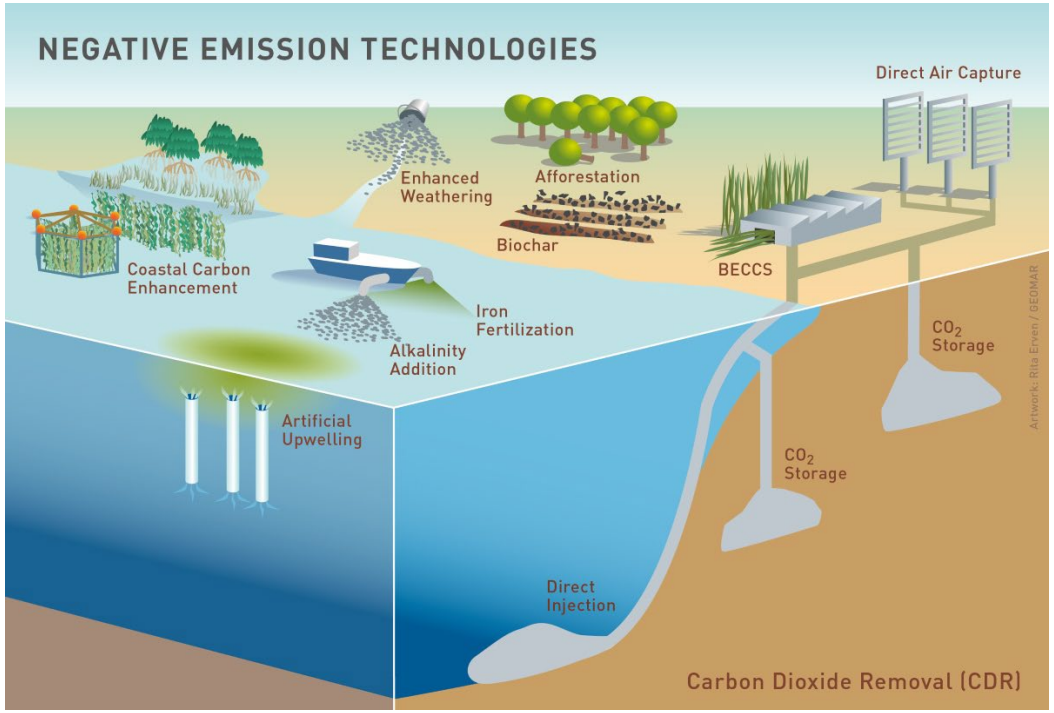
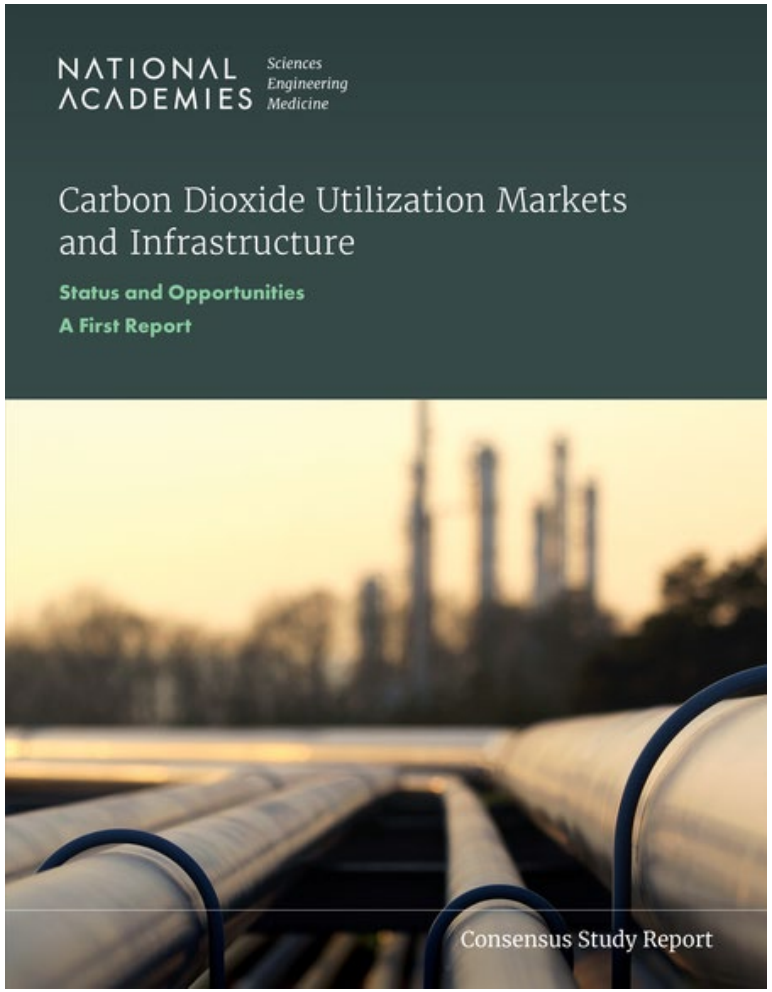


Image: Physics World

Any CDR approach must be net-negative on a lifecycle basis

CO_2 Utilization



NASEM Report, Dec. 2022

CO_2 utilization = chemical transformation of CO_2 into a product with market value
Not enhanced oil recovery or beverages; soil carbon or terrestrial biomass; non-CO_2 carbon sources (e.g. coal)

In chemical industry

Urea synthesis – 12.4 million tons/year in US
Methanol – 2 million tons/year worldwide
Polycarbonates – 600,000 tons/year worldwide
Many concepts at low TRL (e.g. SAF) – almost all require H_2

In net-zero future

Quantity of CO_2 captures (point source + CDR) likely to be much larger than capacity for CO_2 utilization
Infrastructure for CCUS should largely align with S (= sequestration), not U (= utilization)

How to think about cost

Goal for CO_2 capture is typically \$100/ton-CO_2
\$100/ton-CO_2 = \$0.10/kg-CO_2
cf. \$1000/ton-H_2 = \$1/kg-H_2 (Earthshot goal)

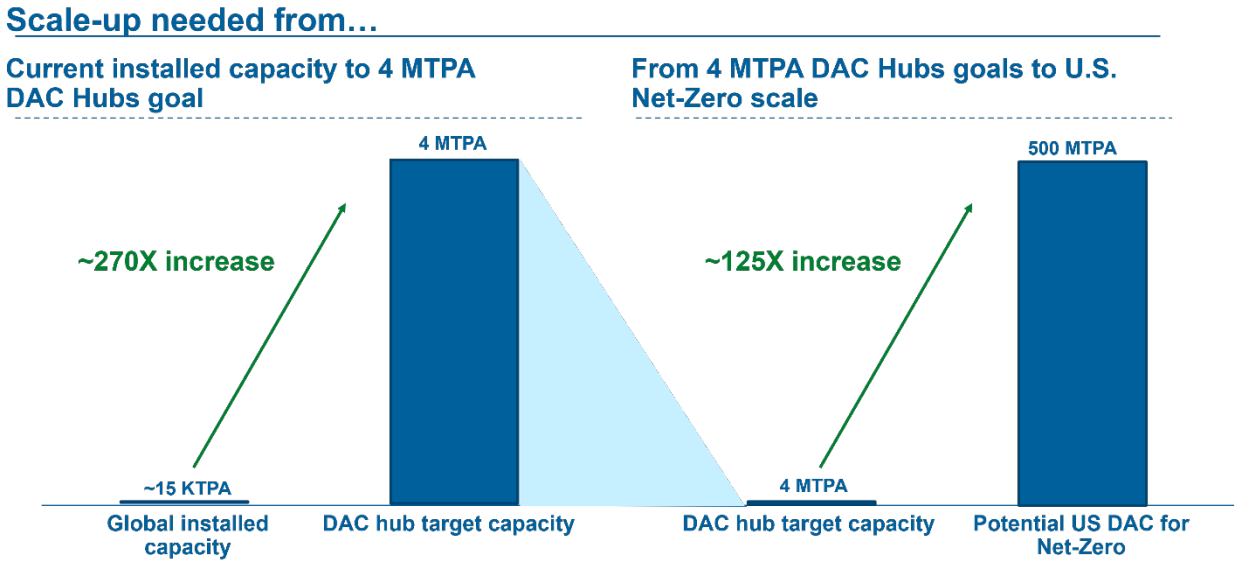
CDR Example 1: Direct Air Capture (DAC)

Key concept

Flow large volumes of air over a device that captures and concentrates CO_2
Sequester CO_2 in underground reservoirs (similar to point-source CO_2 capture)

Current development trajectory

DOE Office of Clean Energy Demonstrations DAC Hubs



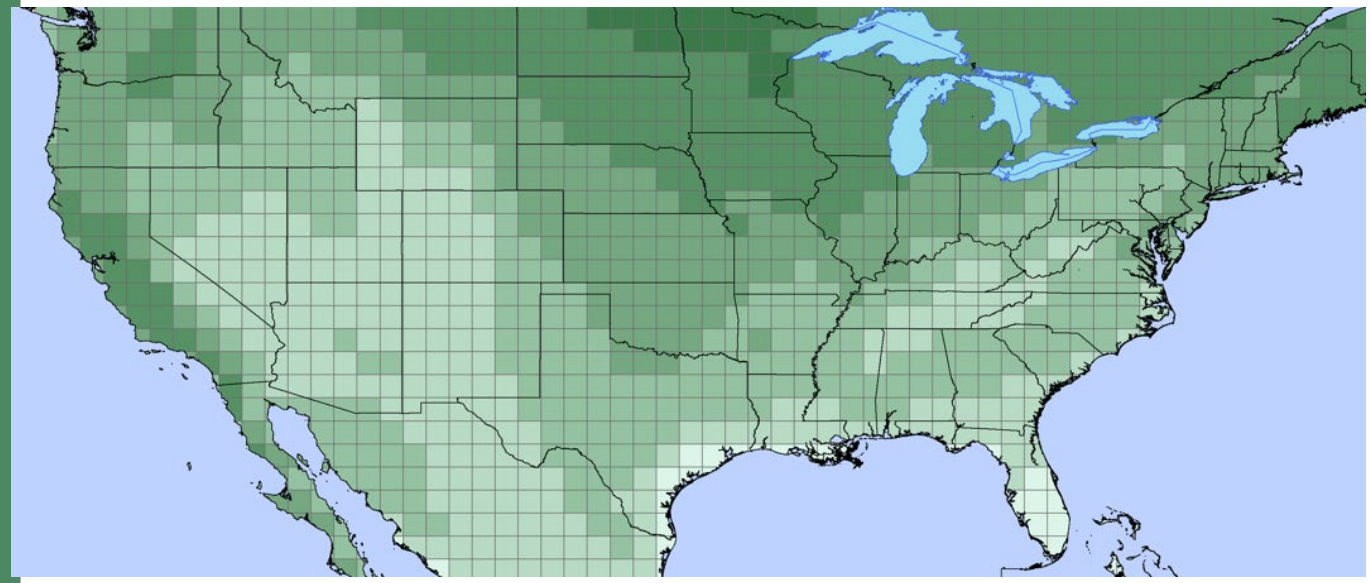
What are key uncertainties?

Cost of process at scale (must be viewed as a large-scale chemical process)
Impacts of siting decisions

Siting Decisions for Standalone DAC

Work with Melissa Dumas & Kashif Nawaz (ORNL)

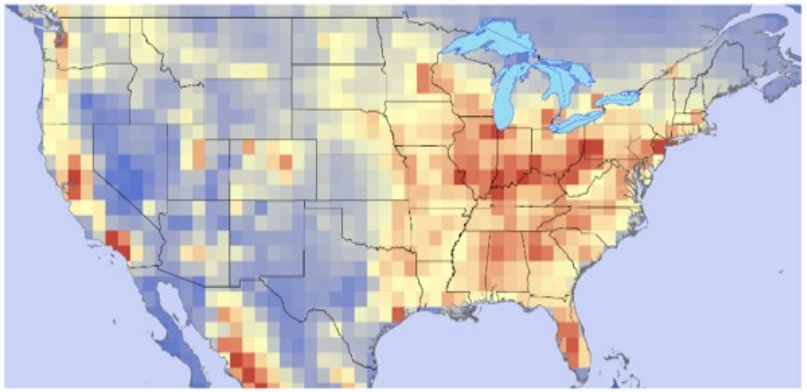
DAC Performance for Fixed Process Conditions
(Adsorption-based process of Elfving et al., Chem. Eng. Sci. 2021)



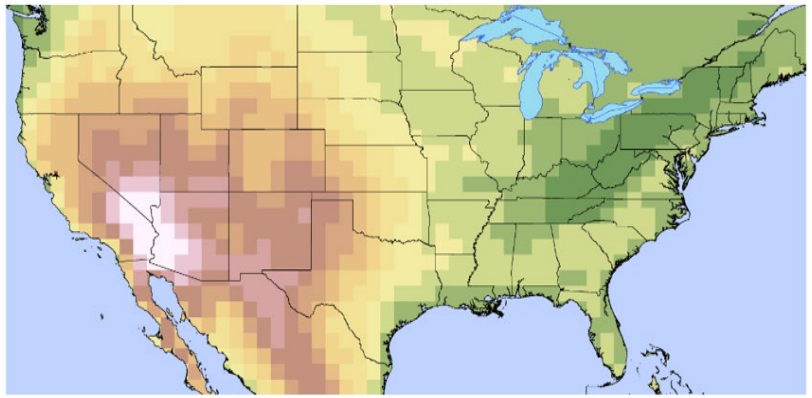
Productivity (mol/kg sorbent • hr)

- < 1.00
- 1.01 - 1.05
- 1.06 - 1.10
- 1.11 - 1.15
- 1.16 - 1.20
- 1.21 - 1.25
- 1.26 - 1.30

CO_2 ppm



Humidity



Optimization of process conditions to reflect temporal and spatial variations changes siting choices

CDR Example 2: Enhanced Weathering

Key concept

Grind silicate minerals then allow to react with CO_2 in air to form carbonate minerals
Spread minerals in natural settings (e.g. agriculture) to accelerate CO_2 capture
Other variations aim to make products (e.g. concrete)

Current development trajectory

Scale of field trials to date appears to be limited

What are key uncertainties?

Natural environments are complex, so estimating CO_2 capture rates at scale is challenging
Verification of CO_2 capture in distributed, natural environments is difficult
Lifecycle emissions associated with obtaining and transporting input minerals must be carefully assessed

CDR Example 3: Biochar/Biomass Storage

Key concept

(i) Convert biomass to biochar, then distribute in natural environments (e.g. soil amendment)
(ii) Store biomass in abiotic environments, preventing decay of captured carbon

Current development trajectory

Biochar has been extensively studied in agriculture, but often in controlled settings
Biolandfill ideas have been proposed (e.g. Yablonovitch, Proc. Natl. Acad. Sci. 120 (2023) e2217695120), but lack long-term demonstrations

What are key uncertainties?

Natural environments are complex, so estimating CO_2 storage/release rates at scale for biochar challenging
Generating biochar requires energy inputs and intrinsic cost
Biomass storage requires ability to maintain and monitor sites for decades

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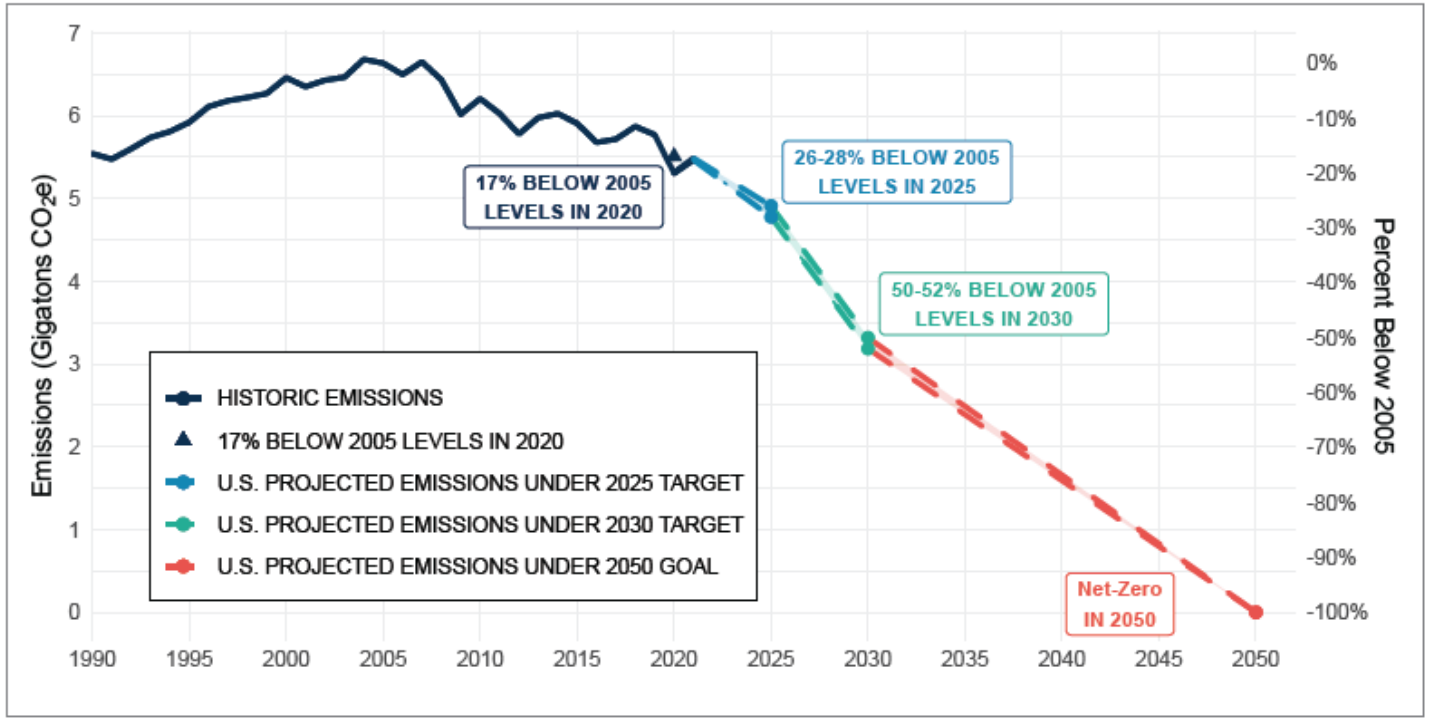

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