Beyond Techno-Economics: Responsible Deployment in Carbon Management

Pete Psarras, Research Assistant Professor, SEAS/KCEP

Penn Climate Week, October 10th – 14th, 2022

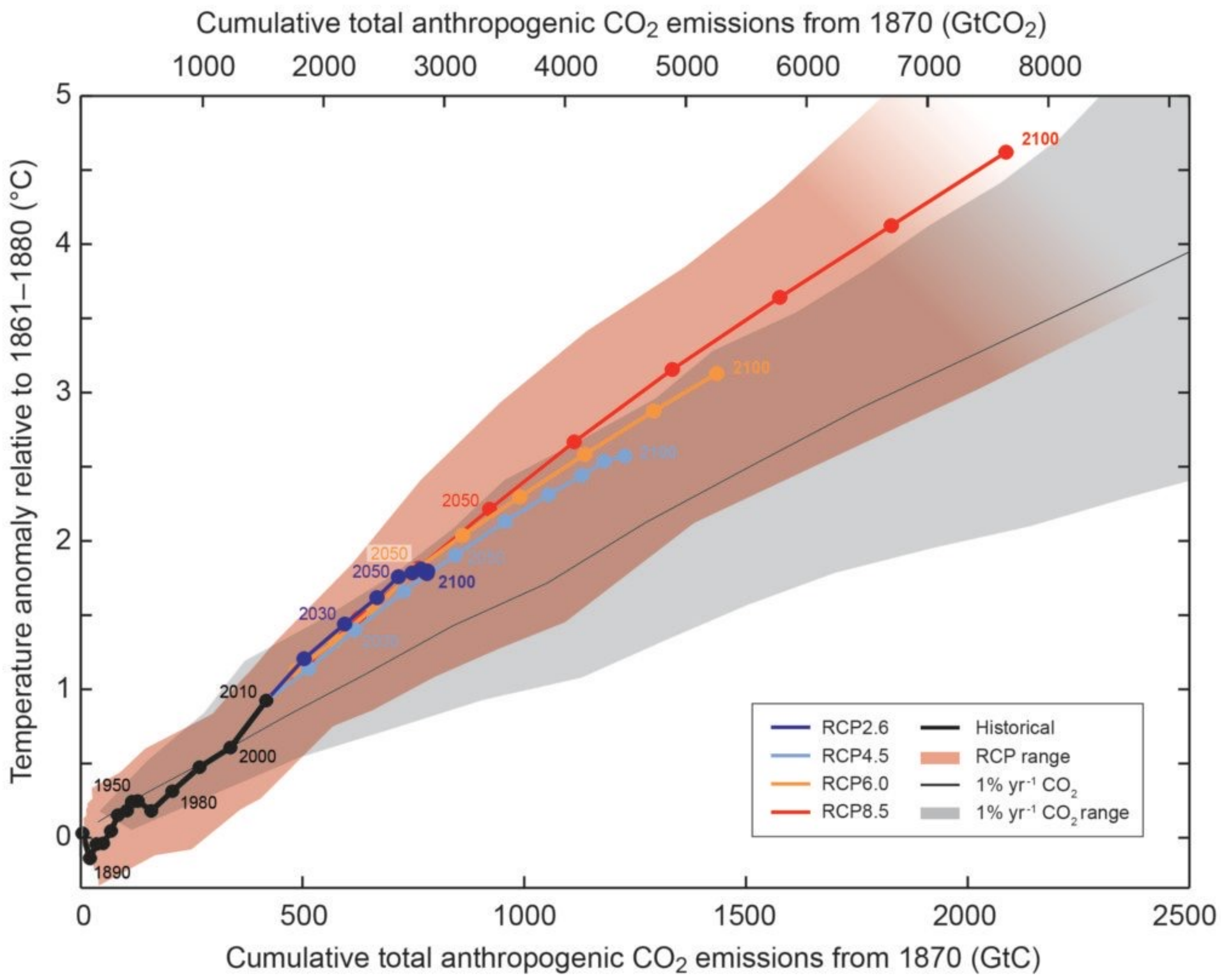
A brief history

2400 $GtCO_2$ (+/- 240 $GtCO_2$)
1850 <> 2019

We are here

1870

2050



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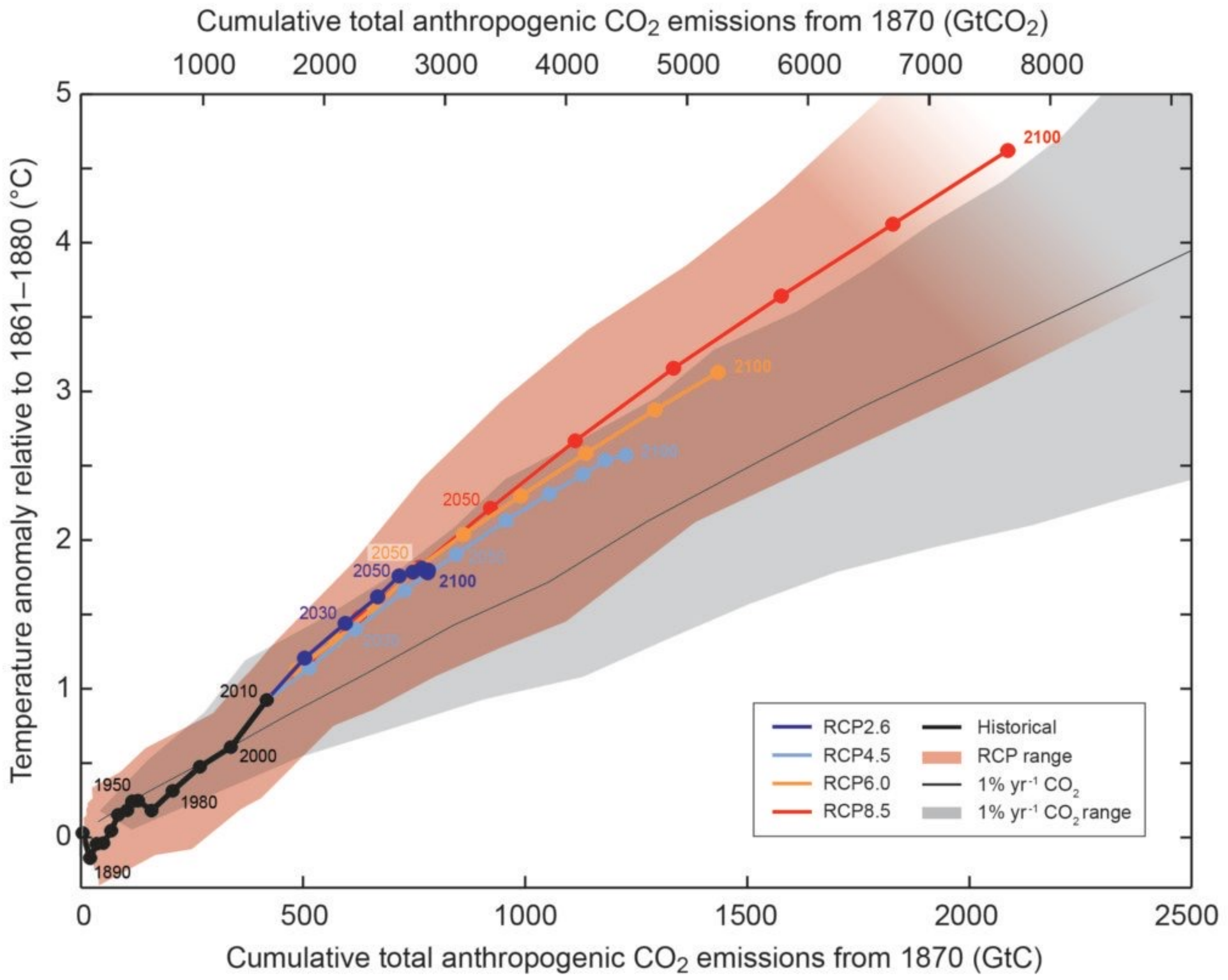
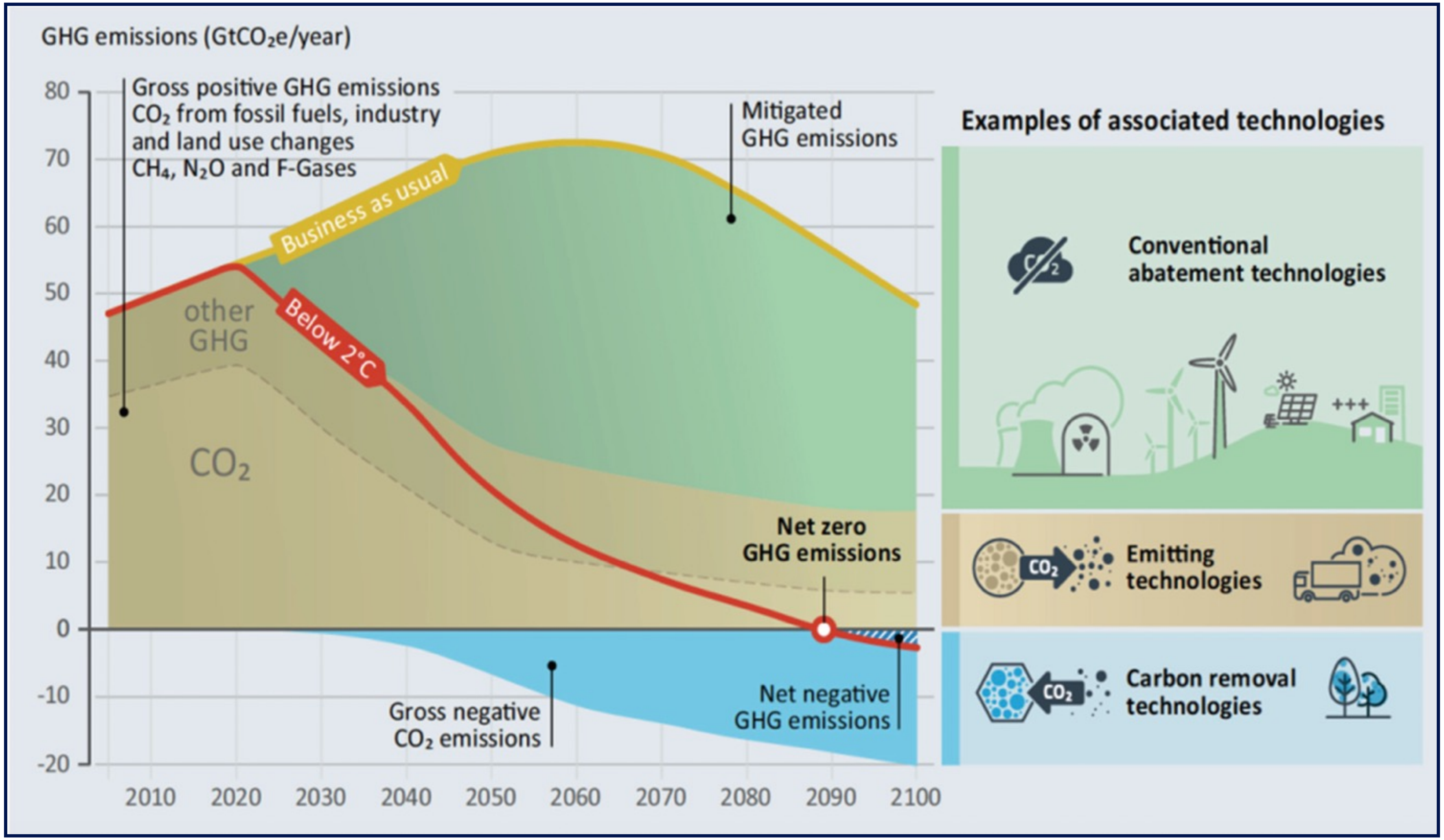
A brief history

Remaining Budget:
500 $GtCO_2e$ (<1.5 ˚C, 50%)
1150 $GtCO_2e$ (<2.0 ˚C, 67%)



The challenge



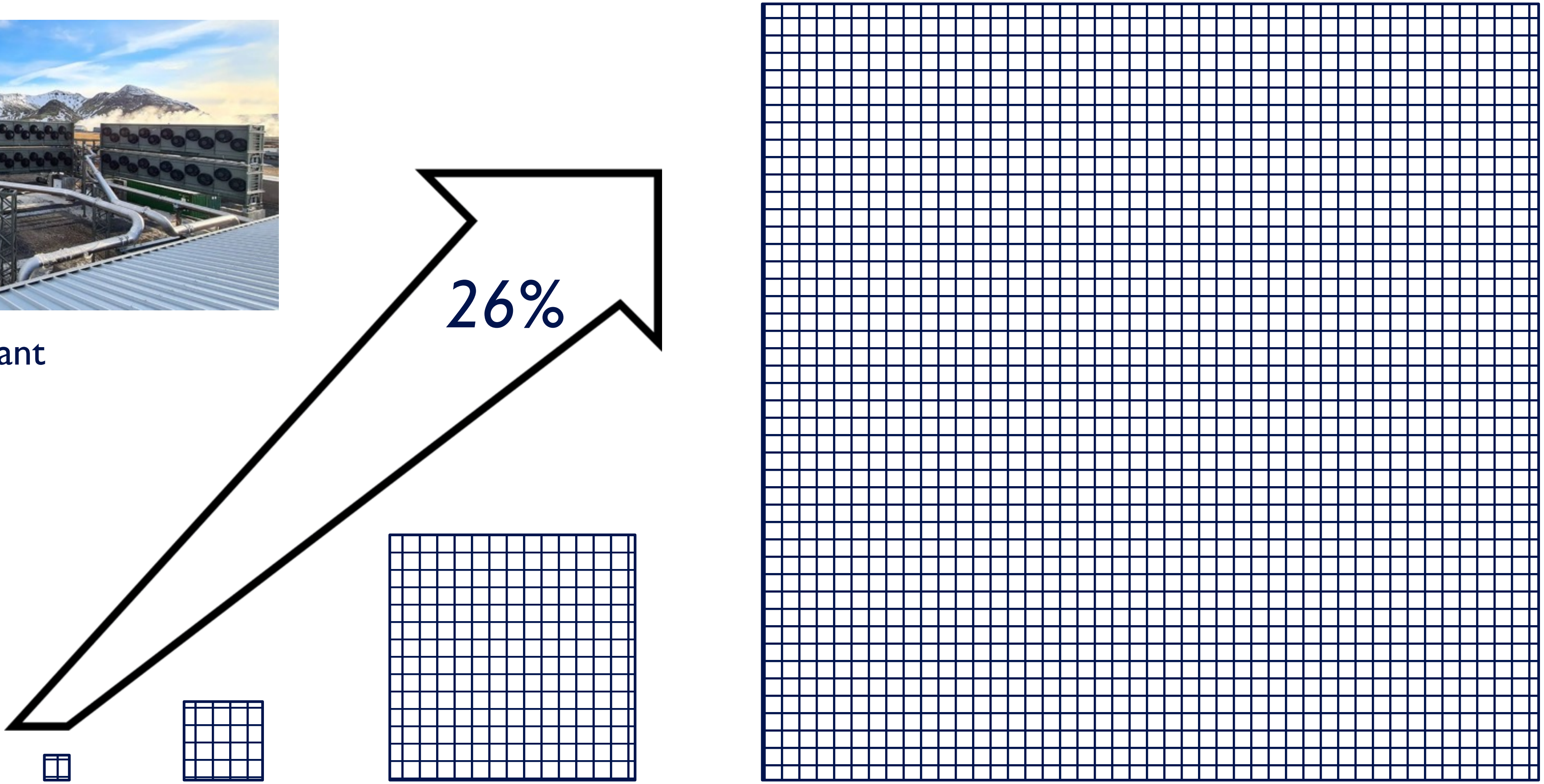
Reduce
Low-carbon energy (CSP, PV, wind, geothermal, nuclear, waste heat, biomass)

Avoid
Point source capture

Remove
Nature-based <u>and</u> Engineered methods

Will it scale?

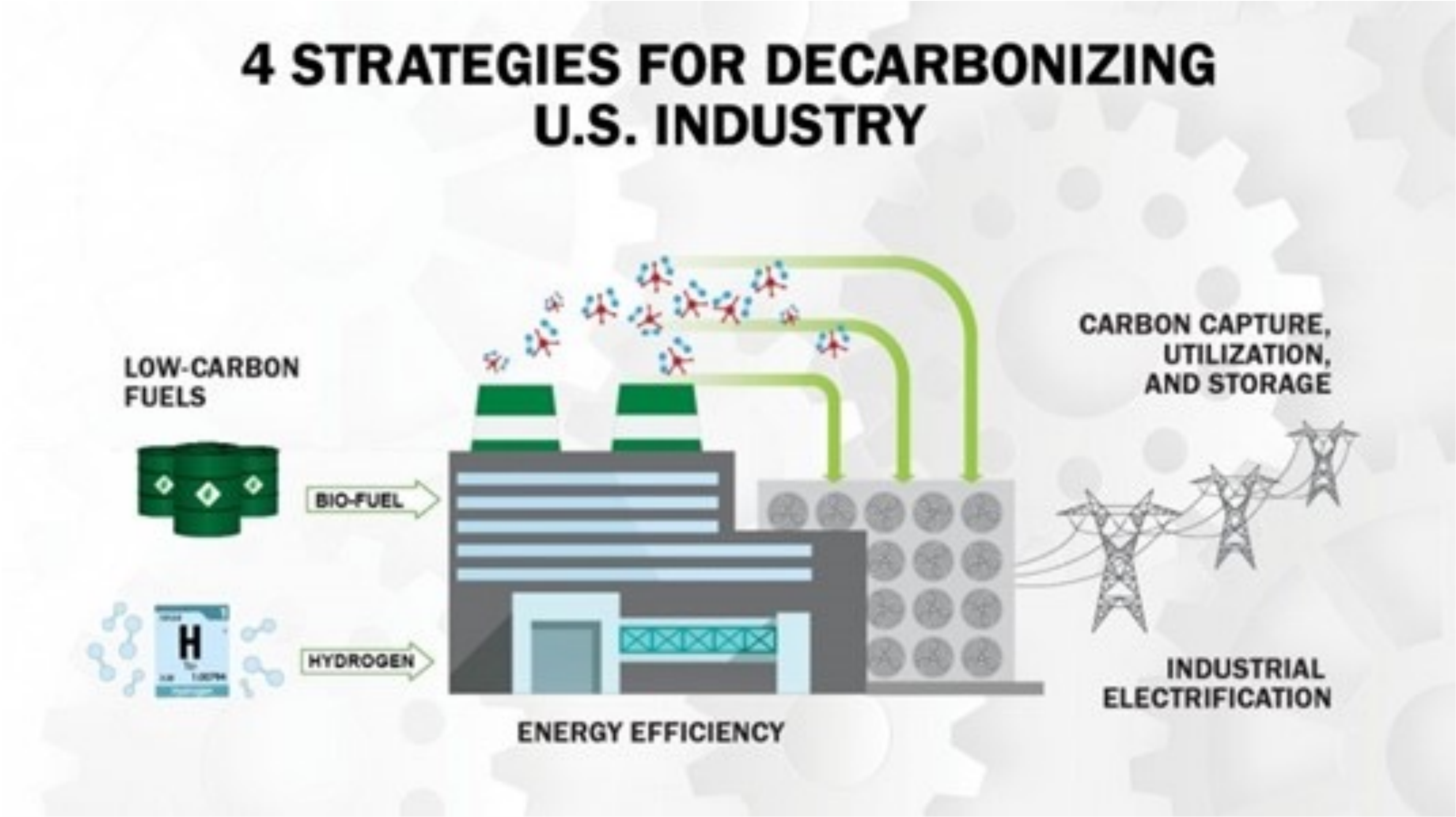
Climeworks “Orca” Plant
cap. = 4,000 tCO_2/yr.



Step 1: **Reduce**

Strategy / **Sector**	Transportation	Electricity generation	Industry	Residential	Commercial	Wastes	Agriculture
Electrification	✓	✓	✓	✓	✓	✓	✓
Reduced use of fossil fuels	✓	✓	✓	✓	✓	✓	✓
Reduce use of highly potent GHGs	✓	✓	✓	✓	✓		
Fuel switching to low-carbon fuels (waste biomass and synthetic fuels)	✓	✓	✓				
Improved efficiency of processes and buildings	✓	✓	✓	✓	✓		✓
Use of high-efficiency heat pumps			✓	✓	✓		
Improved livestock management							✓
Improved land management							✓
Reduced wastes	✓	✓	✓	✓	✓	✓	✓

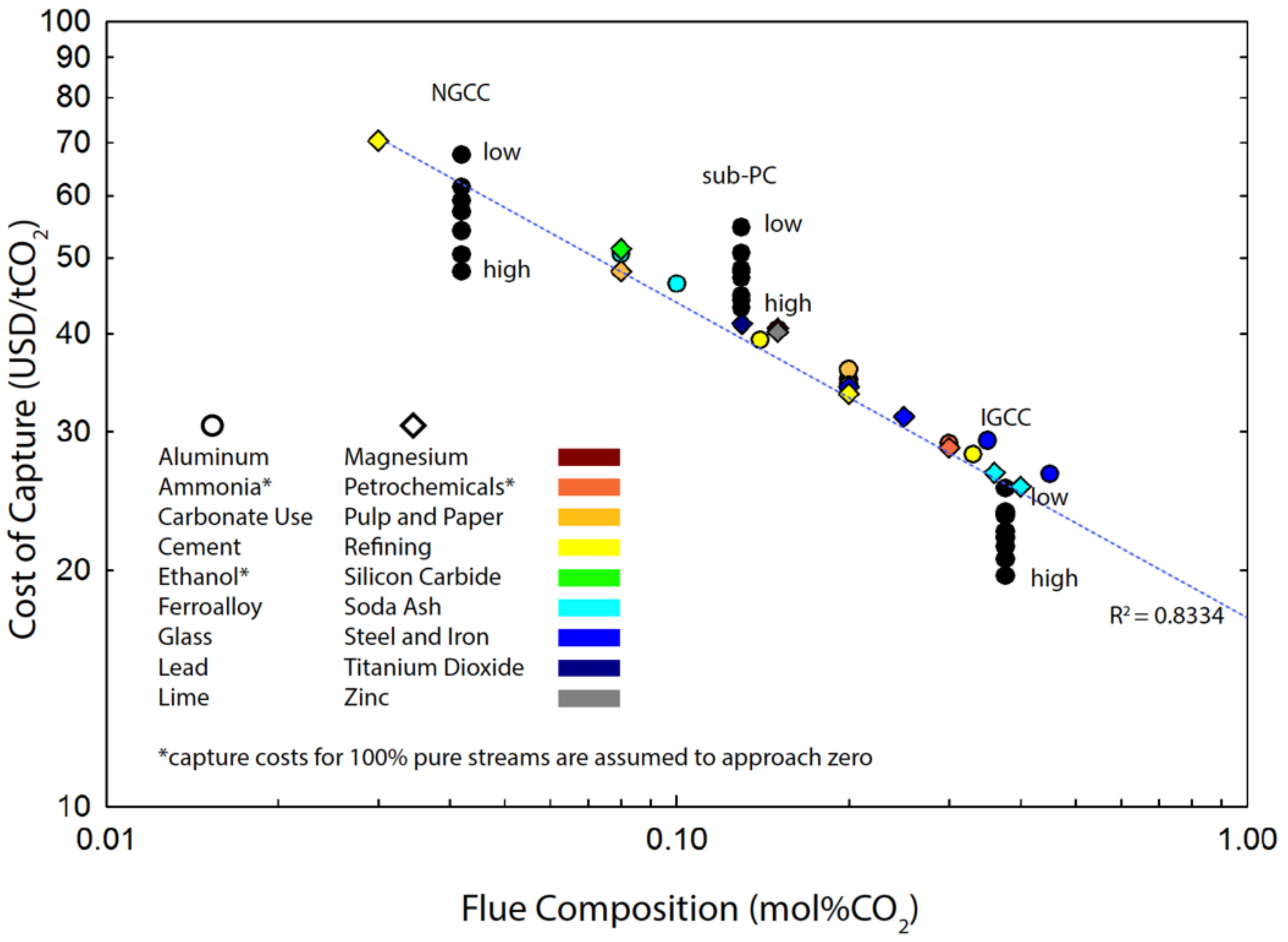
Decarbonizing the industrial sector



https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap

Step 2: **Avoid**

Commodity	Chemistry
Aluminum	$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$
Ammonia	$0.88CH_4 + 1.26air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$
Carbonates	$Ca/MgCO_3 + heat \rightarrow Ca/MgO + CO_2$
Cement	$CaCO_3 + heat \rightarrow CaO + CO_2$
Ethanol	$C_6H_{12}O_6 + yeast \rightarrow 2C_2H_5OH + 2CO_2 + heat$
Ferroalloys	$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$
	$Fe_2O_3 + 2MnO + 5C \rightarrow 2FeMn + 5CO$
	$Fe_2O_3 + 2CrO + 5C \rightarrow 2FeCr + 5CO$
Glass	various components + heat → CO_2 + glass
Iron and Steel	$2C + O_2 \rightarrow 2CO$
	$3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2$
Lead	$2PbO + C \rightarrow 2Pb + CO_2$
Lime	$CaCO_3 + heat \rightarrow CaO + CO_2$
Magnesium	$2MgO + C \rightarrow 2Mg + CO_2$
Petrochem.	$C_2H_4 + 3O_2 \rightarrow 2H_2O + 2CO_2$
H3PO4	$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$
Pulp and Paper	wood organics + $O_2 \rightarrow CO_2$; $CaCO_3 + heat \rightarrow CaO + CO_2$
Refining	$CH_{1.33}O_{0.43} + 0.26O_2 \rightarrow 0.65CH_{1.12} + 0.27H_2O + 0.34CO_2$
SiC	$SiO_2 + 3C \rightarrow SiC + 2CO$
Soda Ash	$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$
TiO2	$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$
Zinc	$ZnO + CO \rightarrow Zn + CO_2$



Psarras et al. *Environ. Sci. Technol.*, 2017, *51* (19)

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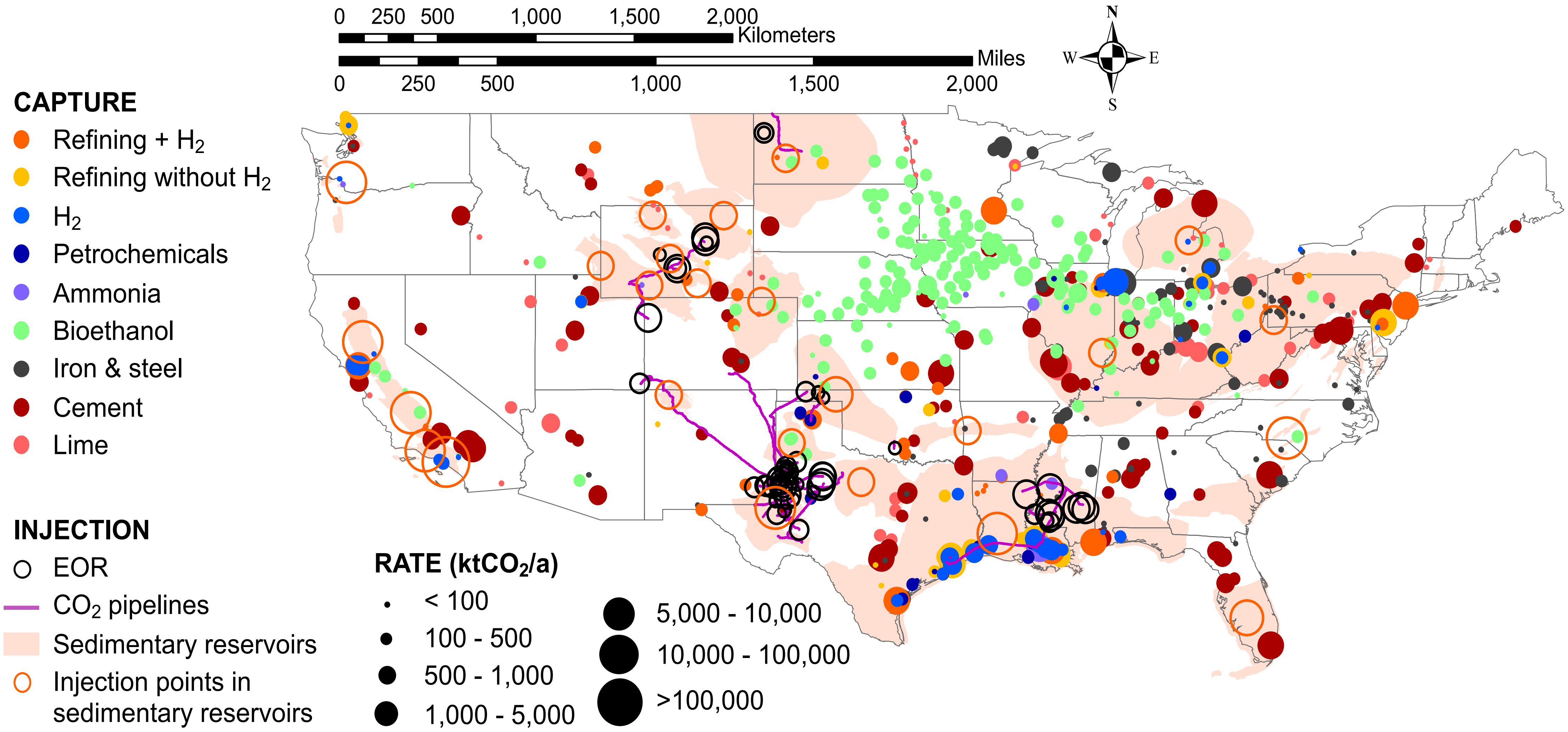
A techno-economic picture of CCS deployment



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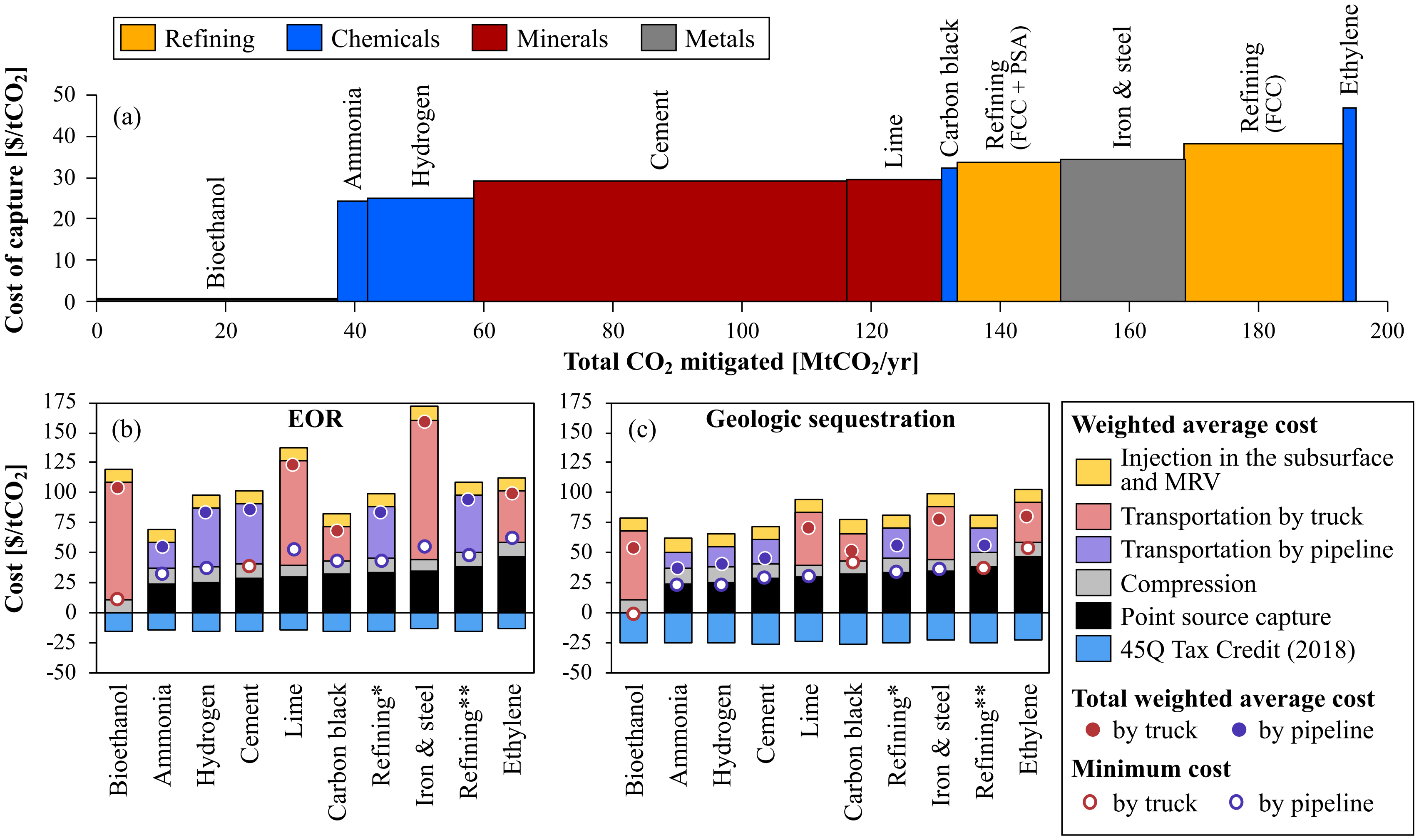
Pilorgé, Psarras, Wilcox, et al., Environmental Science & Technology, 2020

Transportation can significantly shift the merit-order of CCS



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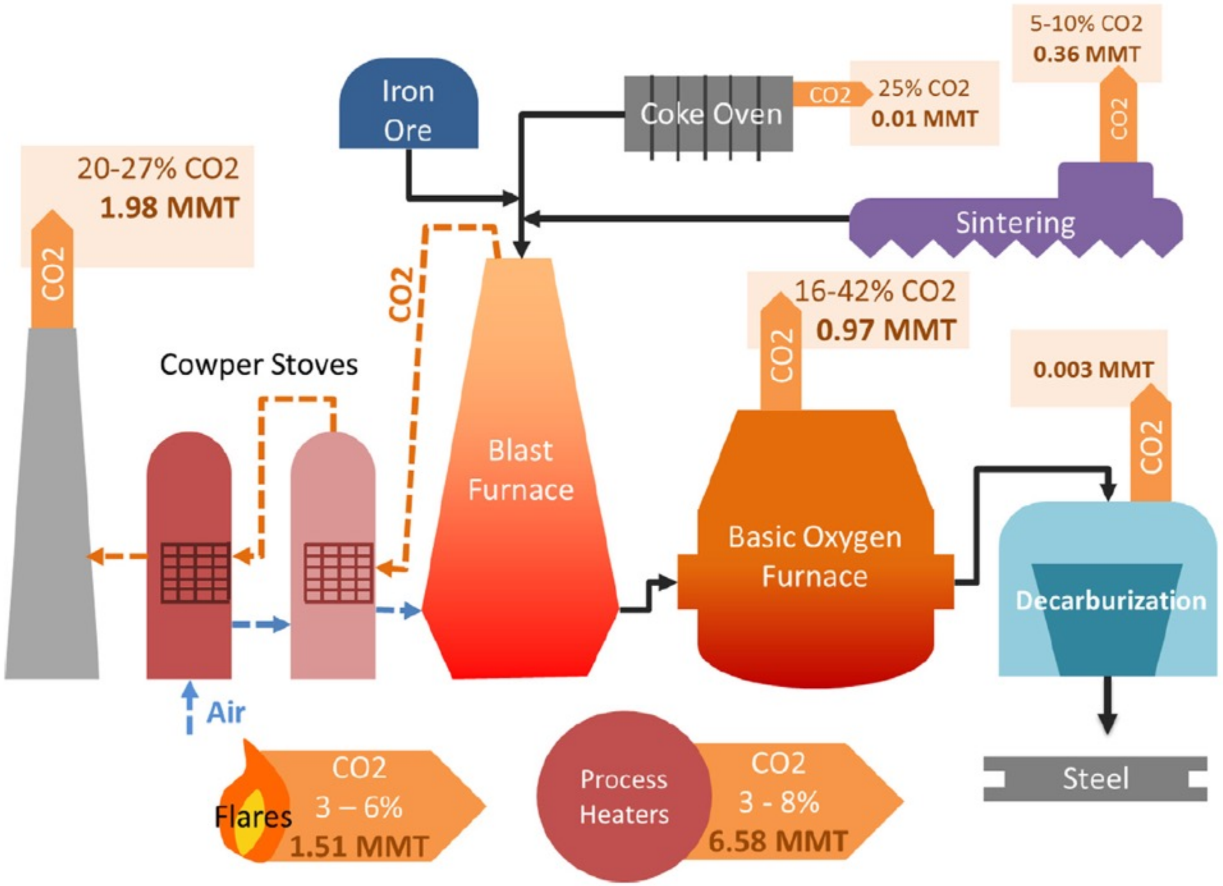
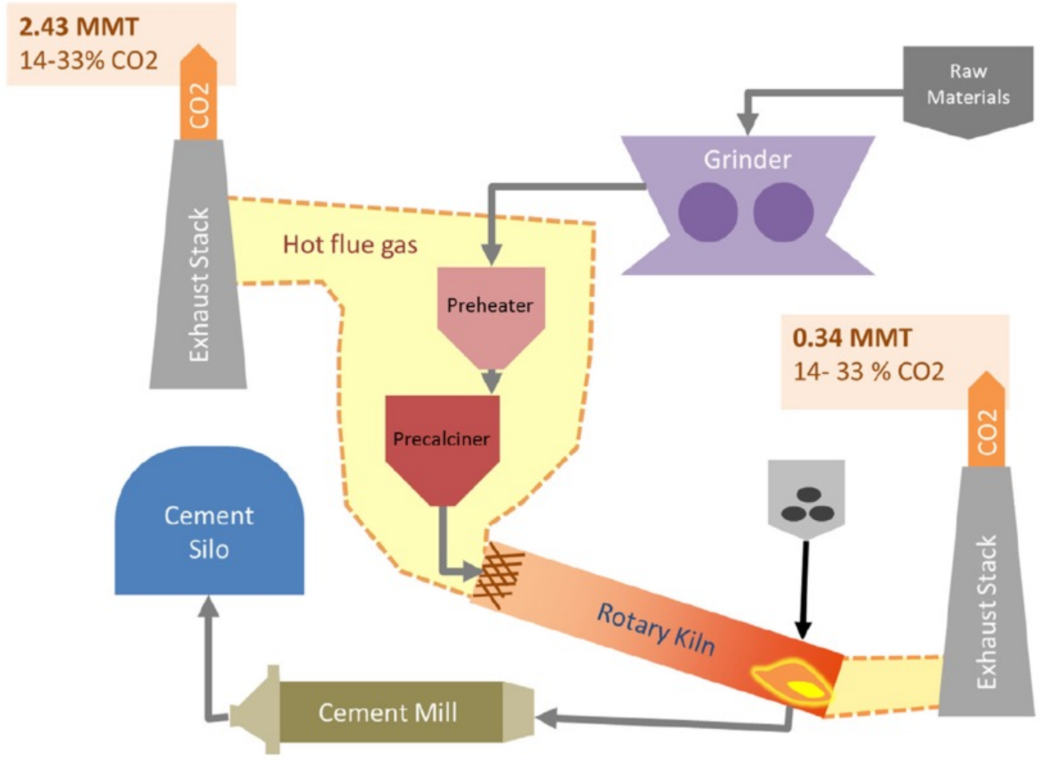
Pilorgé, Psarras, Wilcox, et al., Environmental Science & Technology, 2020

Some industries are more challenging than others

Steel Production



Cement Production



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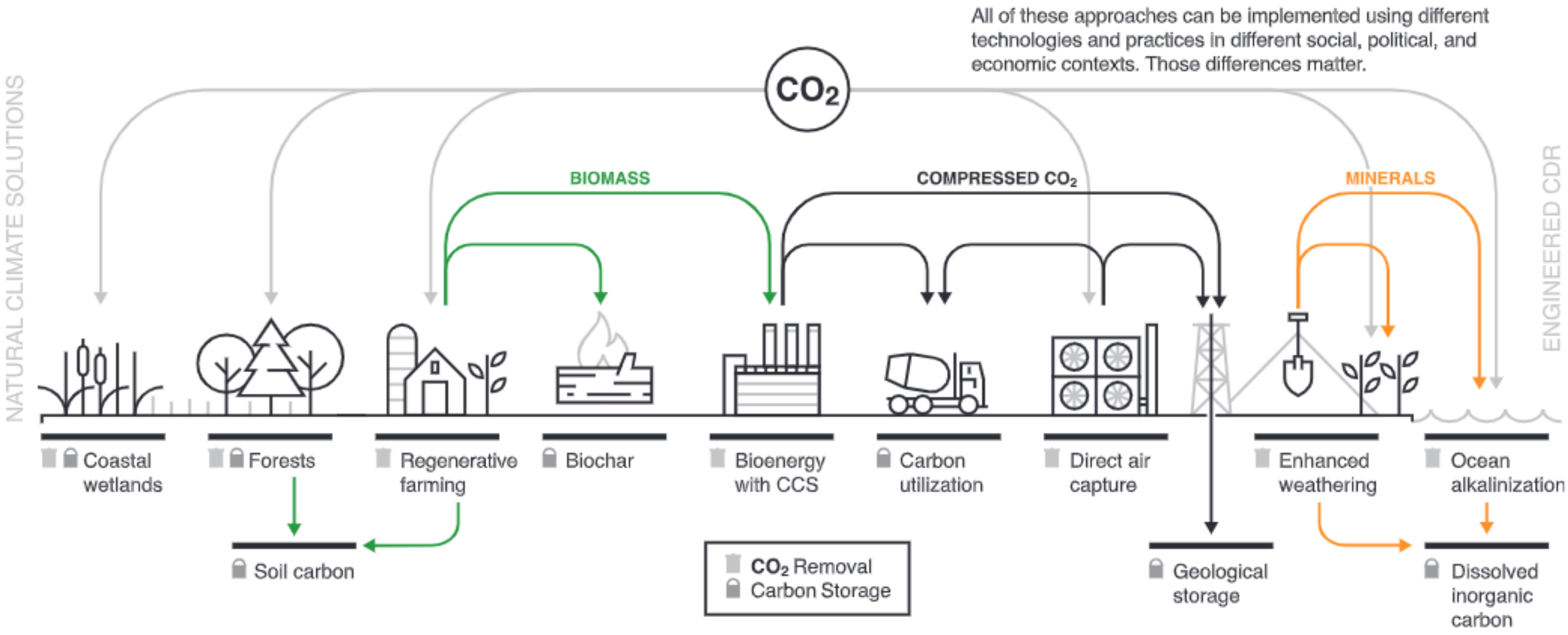
Bains, Psarras, and Wilcox. *Progress in Energy and Combustion Science* 63(2017)146–172

Step 3: **Remove**

near term ⟷ *long term*

lower net CO_2 | counterbalance hard-to-abate residuals | stabilize temperatures via net-zero



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Five principles for quality removal

1. Additionality and Baselines

Baselines against which removals are measured should be set conservatively to avoid over-crediting.

Additionality : above and beyond what would have occurred naturally, eg without human intervention

Five principles for quality removal

1. Additionality and Baselines

2. **Durability**

High quality projects should show low risk of reversal through voluntary or involuntary means through 100 years at a minimum.

Five principles for quality removal

1. Additionality and Baselines
2. Durability
3. **Leakage**

High quality projects should have minimal risk of displacing activities that would result in increased GHG release elsewhere, or at least account for such effects conservatively

Five principles for quality removal

1. Additionality and Baselines
2. Durability
3. Leakage
4. **Carbon Accounting Method**

High quality projects quantify and monitor net carbon removal(and all GHG fluxes) repeatedly and through verifiable methods. Must be transparent about uncertainty

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Five principles for quality removal

1. Additionality and Baselines
2. Durability
3. Leakage
4. Carbon Accounting Method
5. **Do no harm**

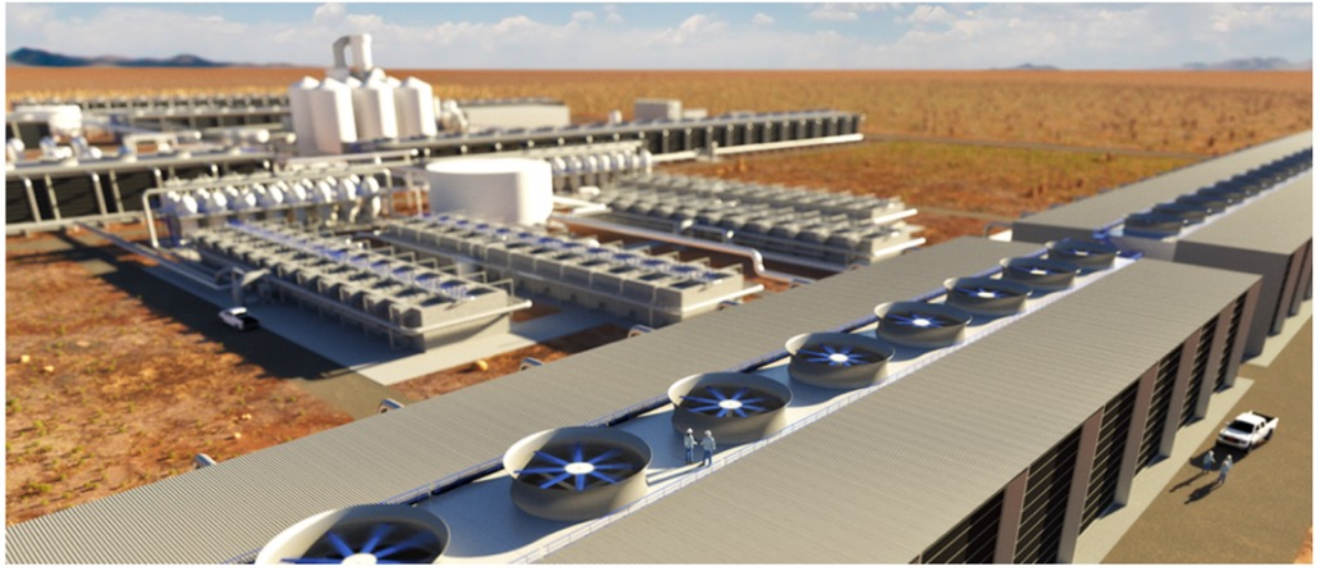
High quality projects must have low risk of any material negative impacts on surrounding ecosystems and communities

Q: Where should we place CDR projects?

A: Where are they technically and economically feasible?

Where are they socially and environmentally acceptable?

Direct Air Capture



Tech	Land (1Mt)	Energy (MW)	Water (t/tCO_2)
Sorbent (right)	0.5 km^2	270 – 280	~0
Solvent (top)	0.4 km^2	270 – 280	4 - 6

top: climeworks.com

right: carbonengineering.com

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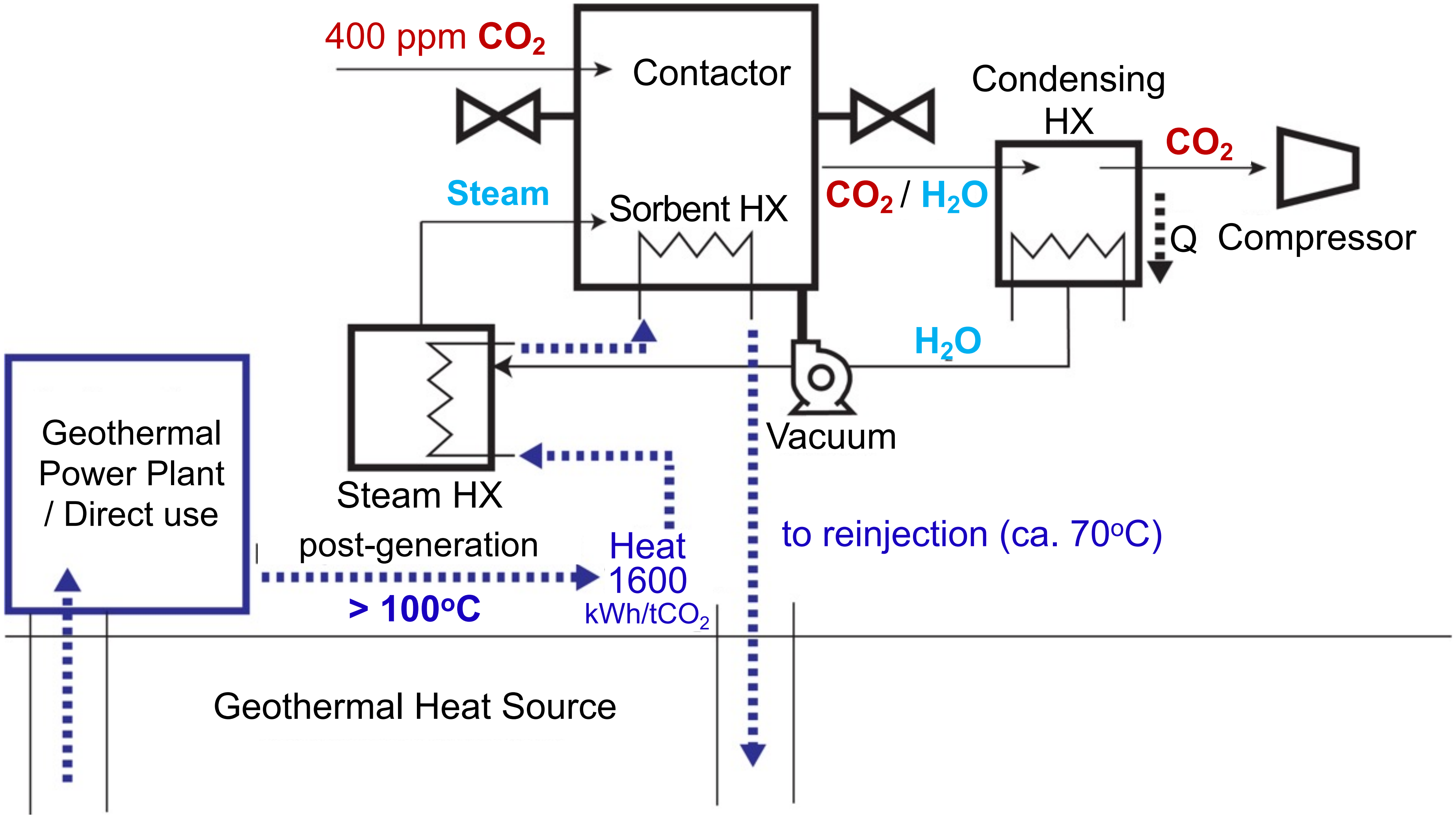
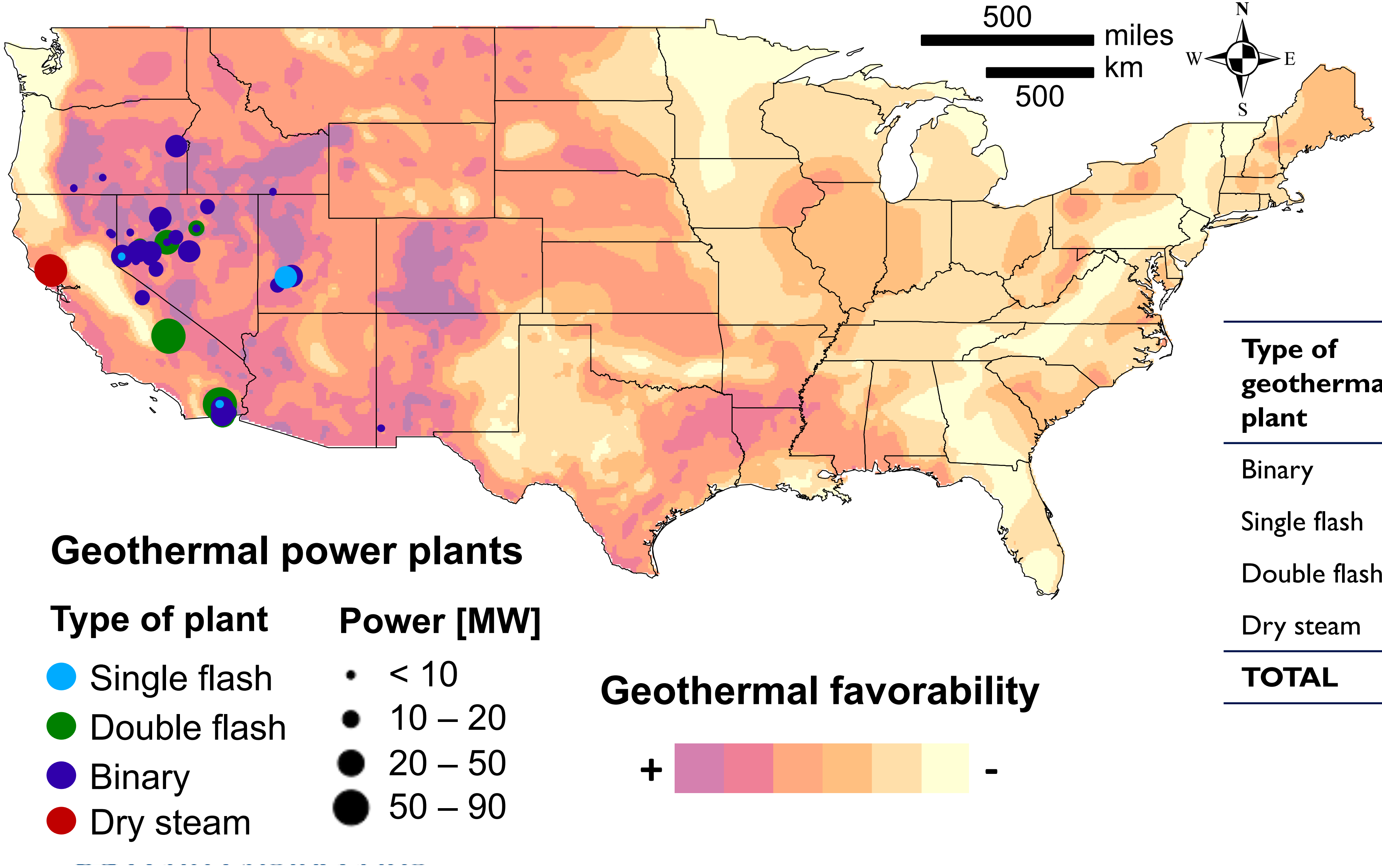
DAC with geothermal energy



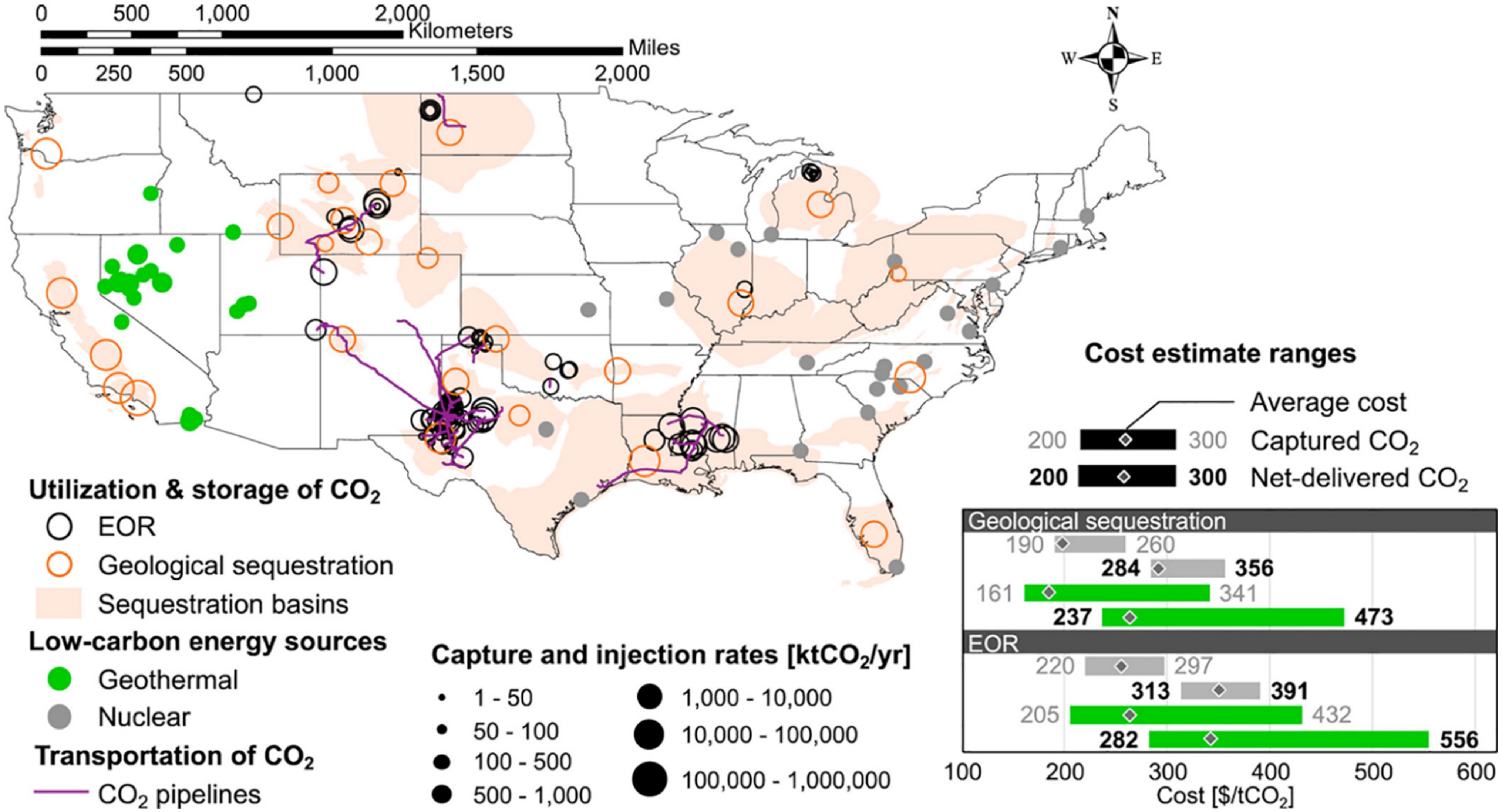
Optimal geothermal resource



Type of geothermal plant	Number of plants	Electric power [MW]
Binary	52	616
Single flash	4	54
Double flash	20	795
Dry steam	18	844
TOTAL	**94**	**2,309**

Source: NREL geothermal prospector

A techno-economic picture of DAC deployment



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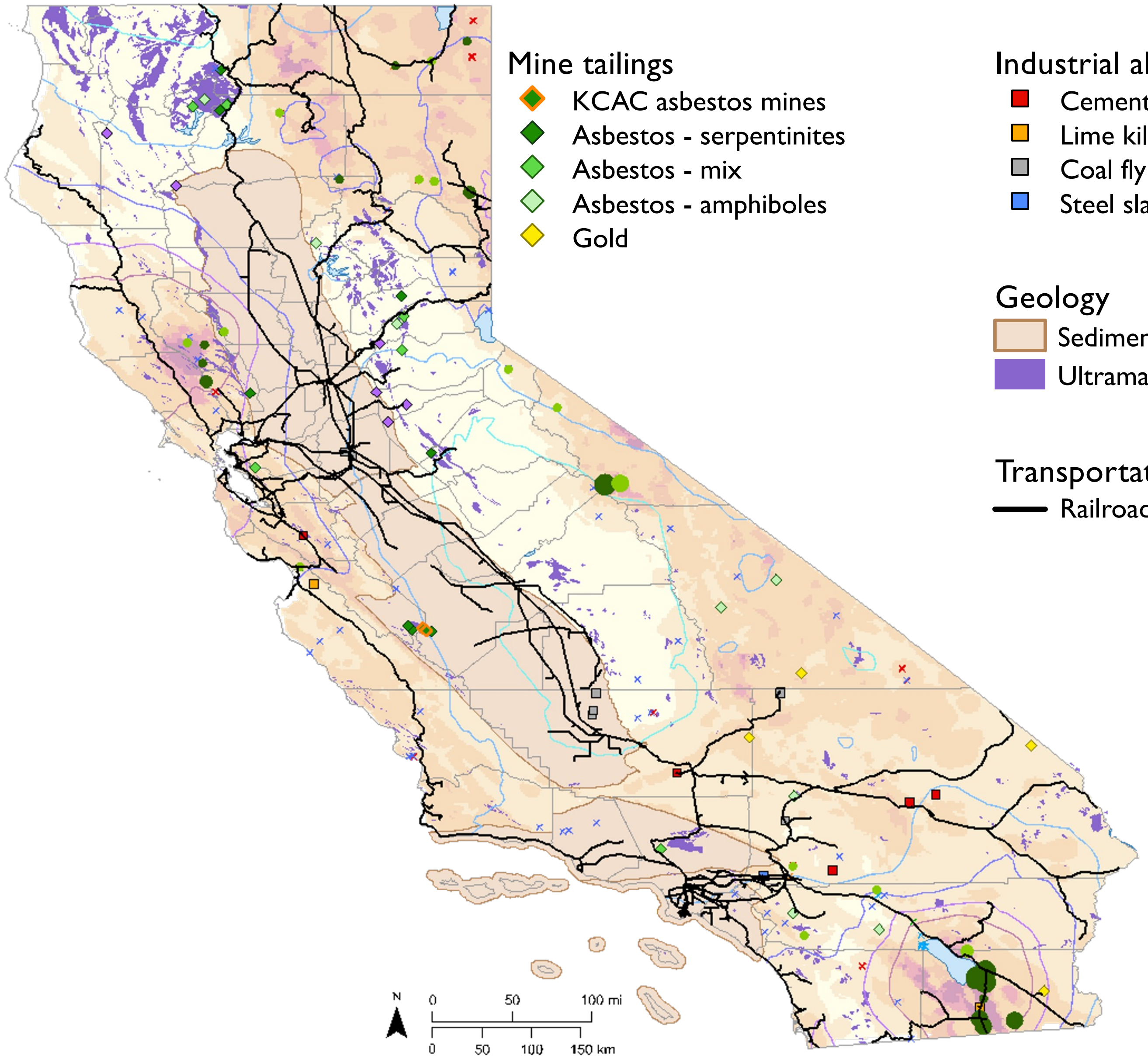
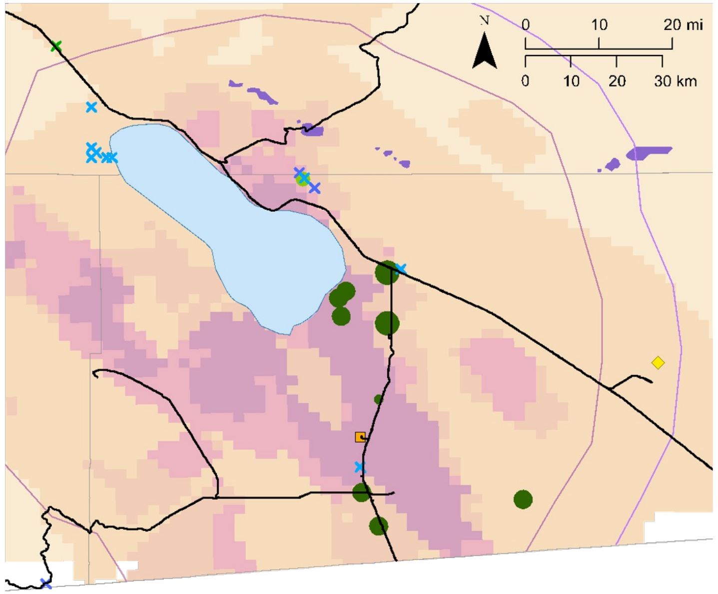
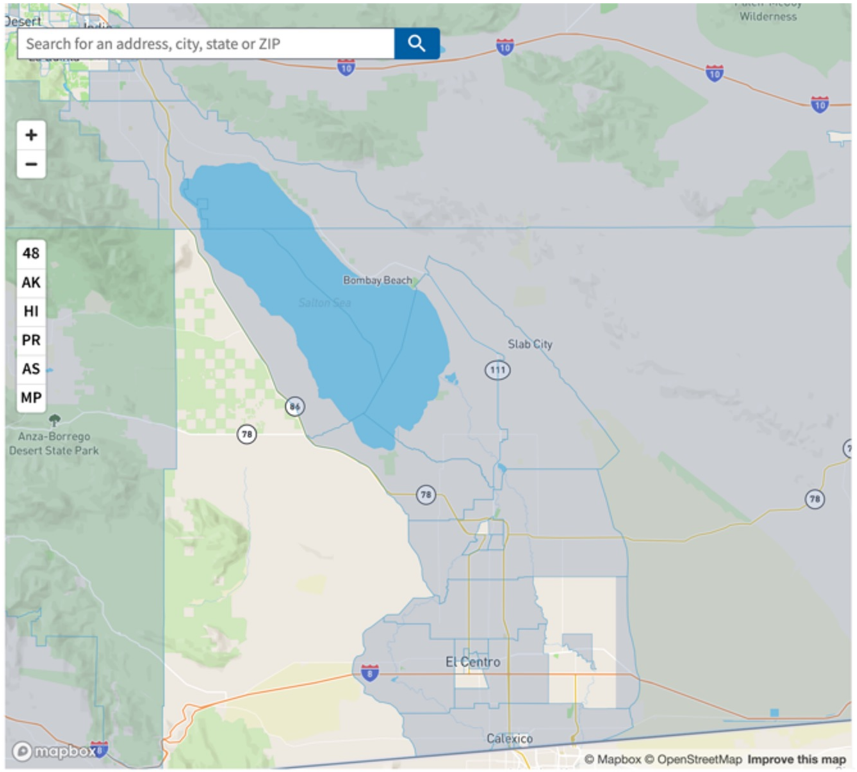
Zooming in…


N
0 50 100 mi
0 50 100 150 km
Mine tailings
KCAC asbestos mines
Asbestos - serpentinites
Asbestos - mix
Asbestos - amphiboles
Gold
Industrial alkalinity
Cement kiln dust
Lime kiln dust
Coal fly ash
Steel slag
Geology
Sedimentary reservoirs
Ultramafic rocks
Transportation
Railroads
Geothermal wells
T>100°C
60<T<100°C
DAC potential [MtCO2/yr]
<50
50-100
100-500
>500
Surface heat flow
0.1
>15
[MW/km2]
Isotherms T=100°C
500 m
1000 m
1500 m
2000 m
2500 m
Direct use
Aquaculture
Resort/pool
District heating
Space heating
Greenhouses


N
0 10 20 mi
0 10 20 30 km

We need more layers…

- DAC
- + geothermal
- + PV
- + wind



https://ejscreen.epa.gov/mapper/

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How should we think about land usage?

Divide land into "environmental exclusion categories"

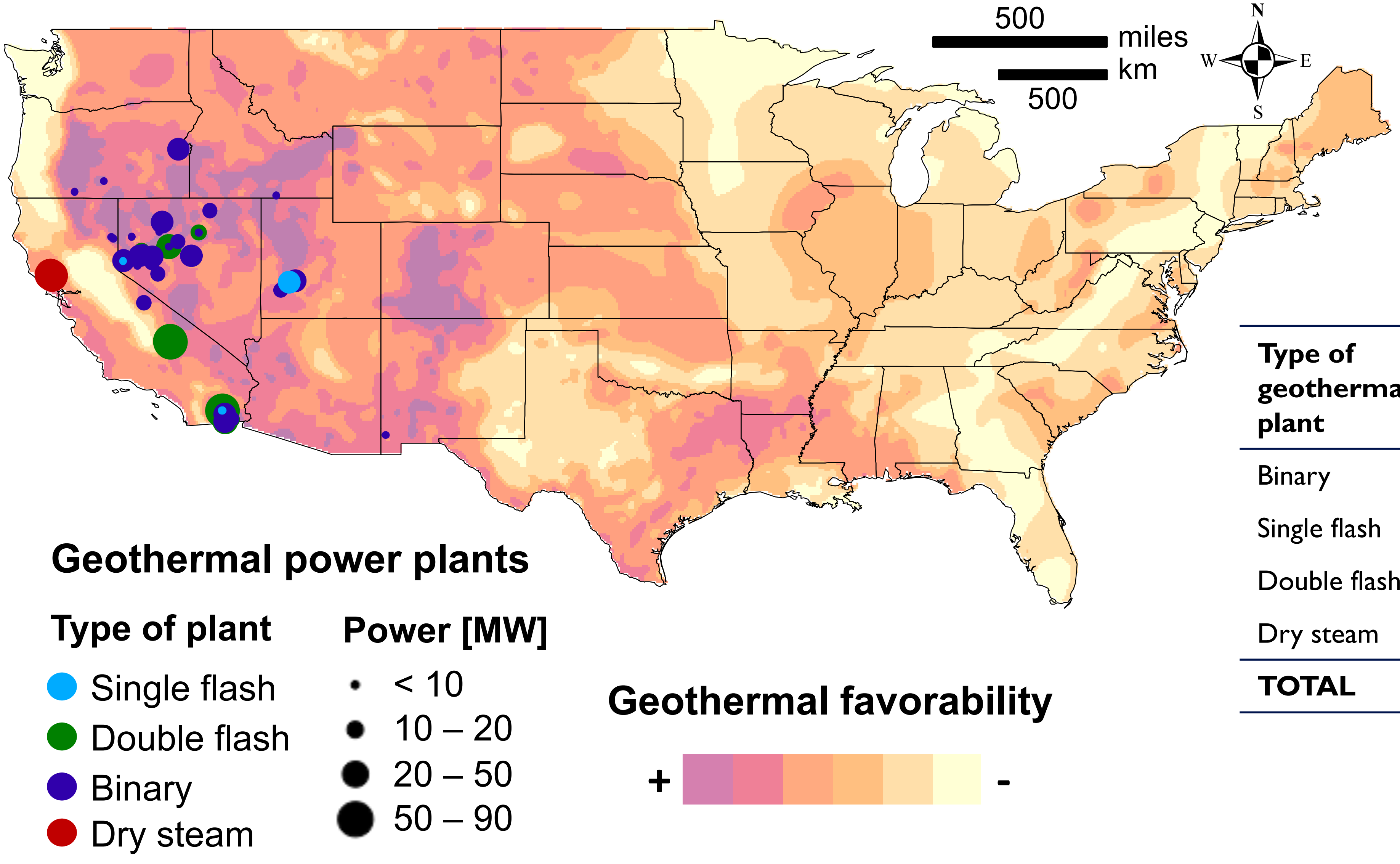
Category 1 (Legally protected): Areas with legal restrictions against energy development. Example: National Wildlife Refuge, National Parks

Category 2 (Administratively protected): Areas where siting requires consultation or review process to protect **ecological values, cultural values,** or **natural characteristics.** Examples: critical habitats for endangered species, tribal lands

Category 3 (High conservation value): Areas that have been determined through multi-state or ecoregional analysis to hold high social, economic or cultural value. Examples: Prime farmlands, important bird areas.

Category 4 (Landscape intactness): Example: wildlife corridors

Revisiting optimal geothermal resource



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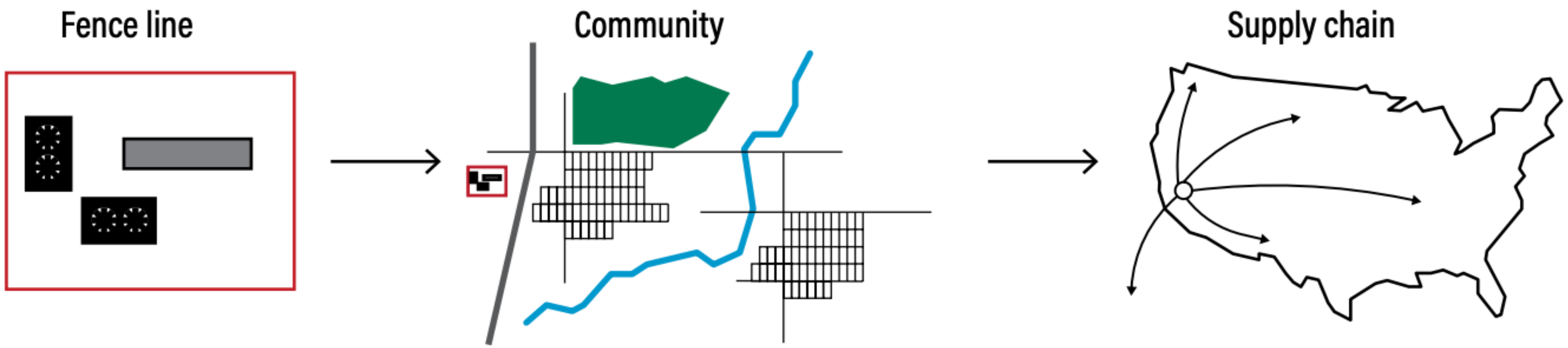
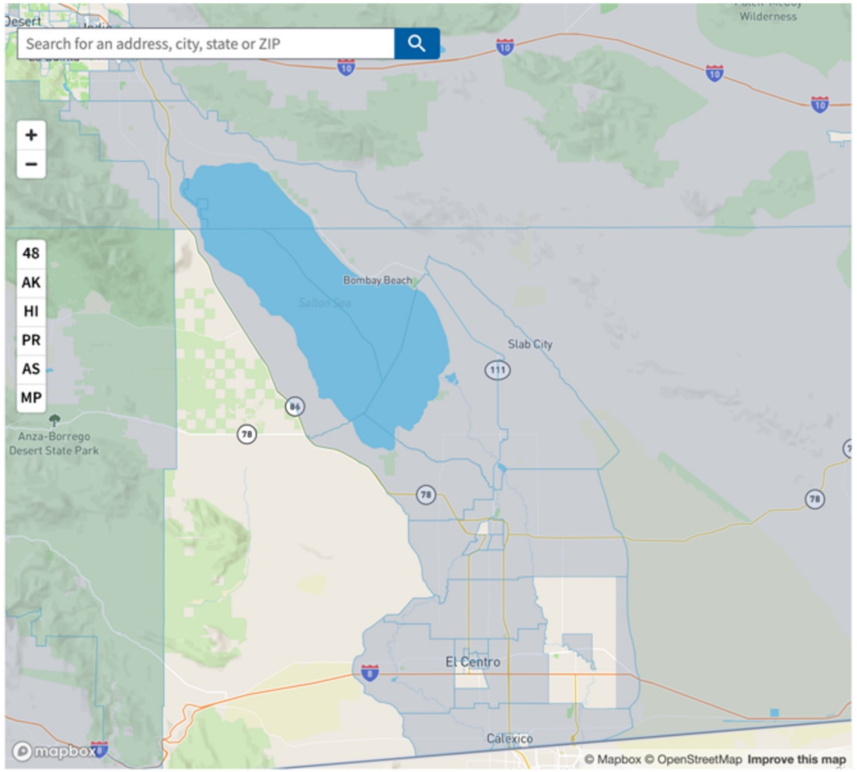
Impacts can occur throughout the value chain



	Local	Distributed
One time: Pre-plant	Construction of plant (one time), construction material production, transport, labor	Production of capture media, production of select construction materials, production of energy infrastructure
Ongoing	Energy usage (fossil), chemical leakage or drift, transport of materials to/from plant, energy production, CO_2 use-related activities,* management of captured CO_2,* end-treatment of plant materials	Distant supply chain stresses; production of capture media; production of electricity, transport, and management of captured CO_2,* end-treatment of materials*
One time: Post-plant	Decommissioning, destruction, post-site maintenance and remediation, destruction and disposal transport, economic loss, discontinuation of CO_2 use-related activities,* end-treatment of materials, residual infrastructure, post-management site care	Economic loss, end-treatment of plant materials, residual infrastructure, post-management site care

Lebling et al. *World Resources Institute, 2022*

Did we miss something?



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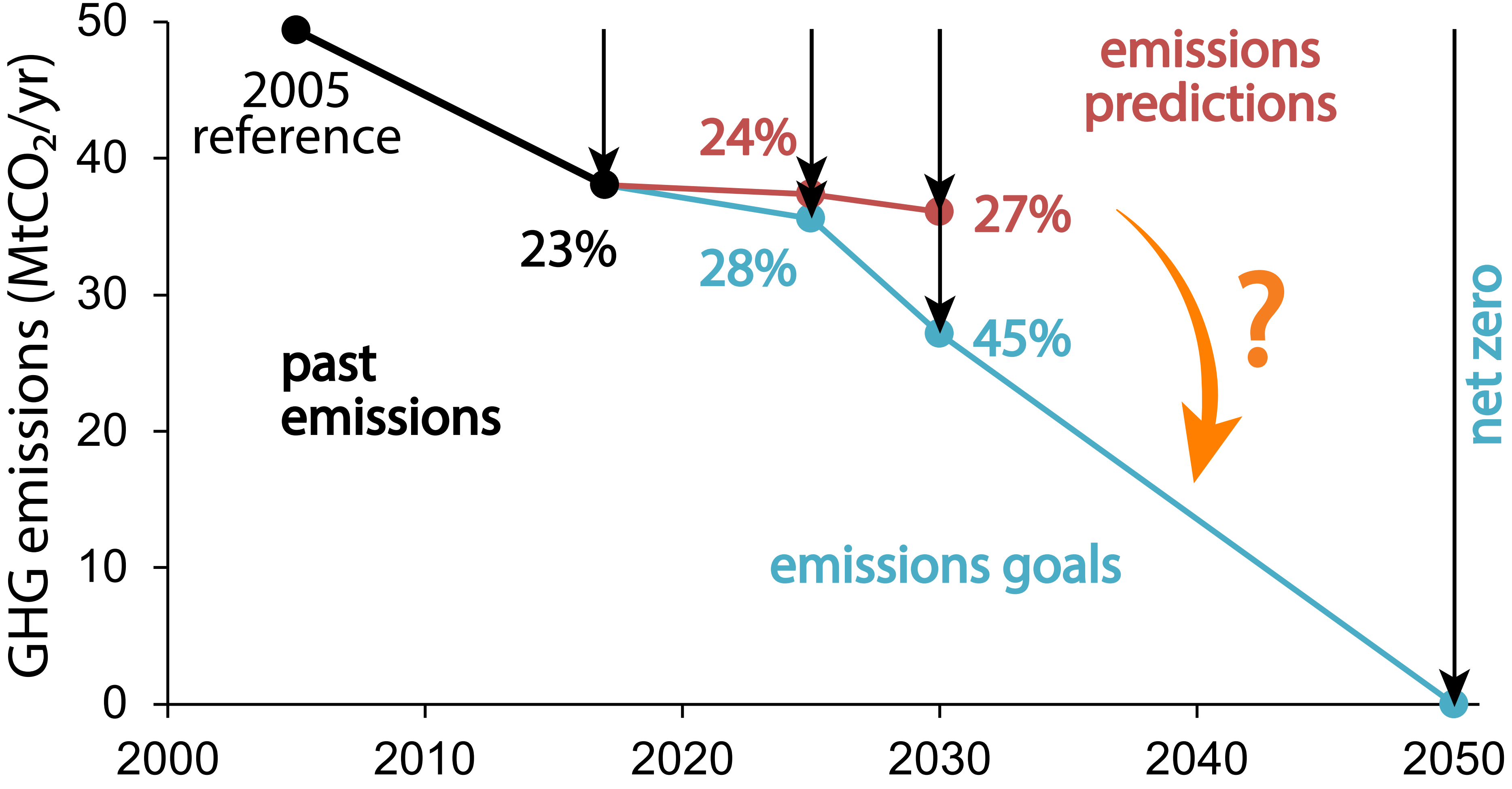
Net-zero Nevada: from pledge into action

The University of Pennsylvania
The Nature Conservancy – Nevada Chapter

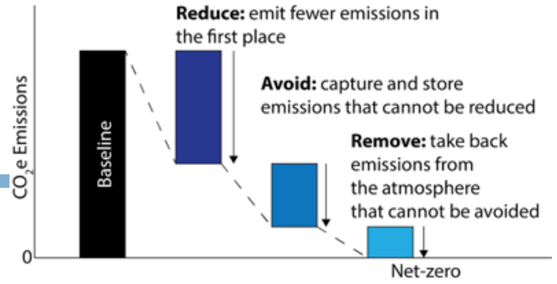
From pledge into action

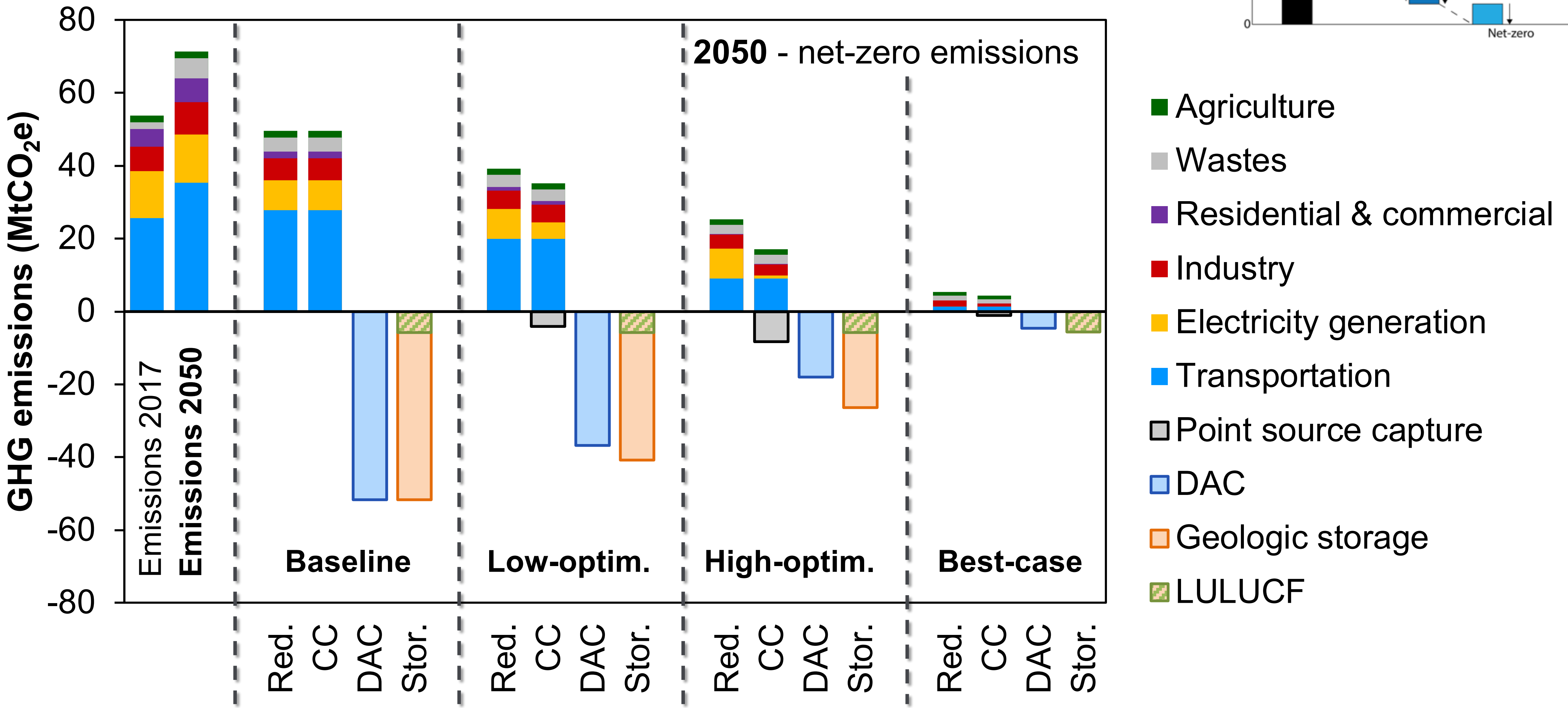


Strategies for deep economy-wide decarbonization

			Baseline	Low-optimistic	High-optimistic	Best case
REDUCE	Transportation	EV penetration – light duty (% of stock)	20%	50%	75%	100%
		EV penetration – heavy duty (% of stock)	5%	10%	20%	60%
		Jet fuel carbon intensity (gCO_2e/BTU)	0.085	0.072	0.058	0.029
	Industry	Electrification compliance (replacing NG use)	60%	75%	90%	100%
	Res. & Comm.	Building units with high-efficiency shells	50%	63%	75%	100%
		Building units with all electric appliances	75%	85%	95%	100%
		Building units with high-efficiency appliances	60%	75%	90%	100%
	Waste	Landfill gas to energy deployment	40%	50%	65%	100%
	Agriculture	Low-till and no-till soil management	0%	35%	60%	100%
		Lower-emitting cattle feed	0%	20%	45%	100%
		Grazing land improvements	0%	10%	25%	50%
AVOID	Electricity gen.	Point source capture at NG power plants	No CC	50% CC	100% CC	All retired
	Industry	Point source capture at industrial facilities	No CC	1 plant	2 plants	All 3 plants

Toward net-zero in 2050

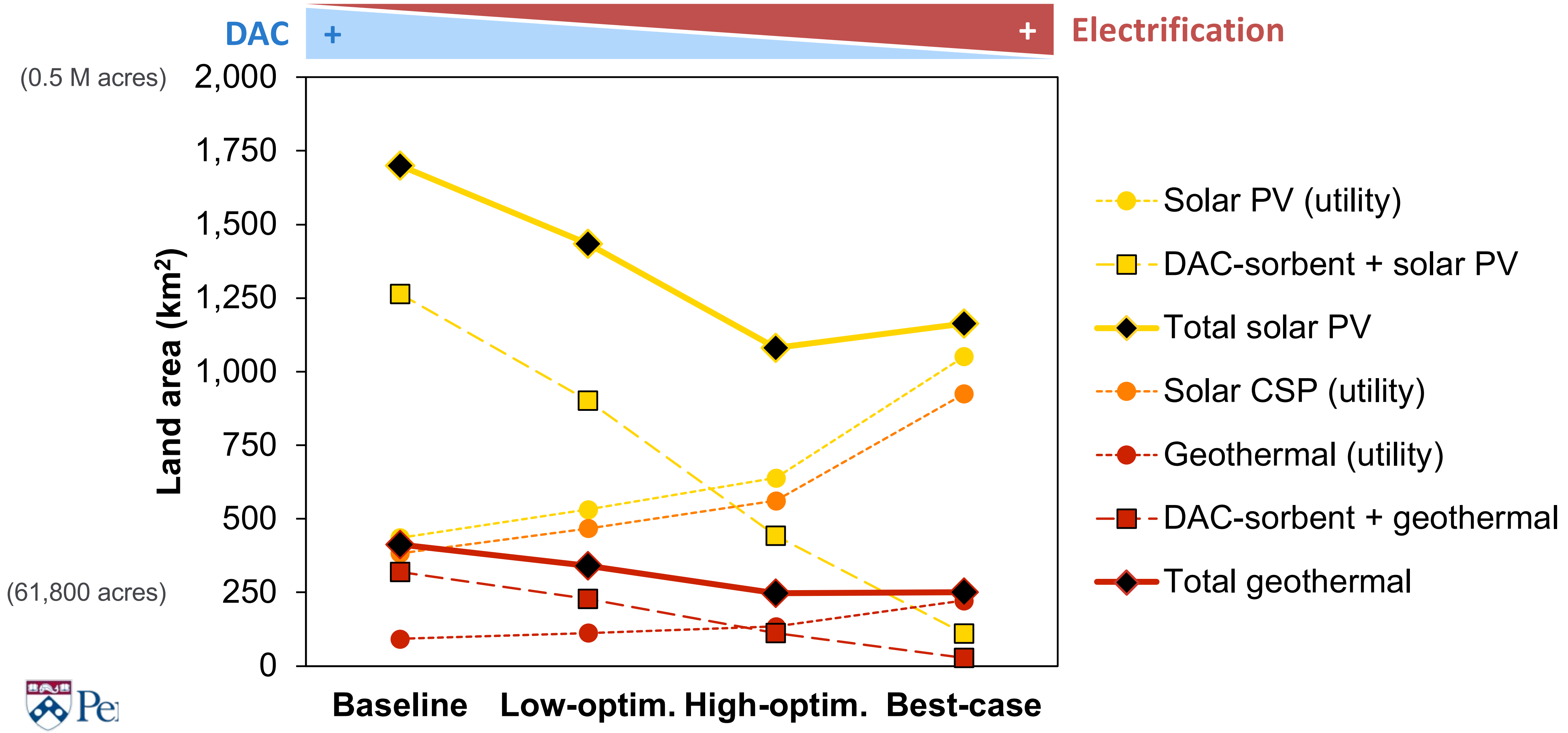




Red. = GHG emissions reduction; CC = carbon capture; DAC = direct air capture; Stor. = CO_2 storage

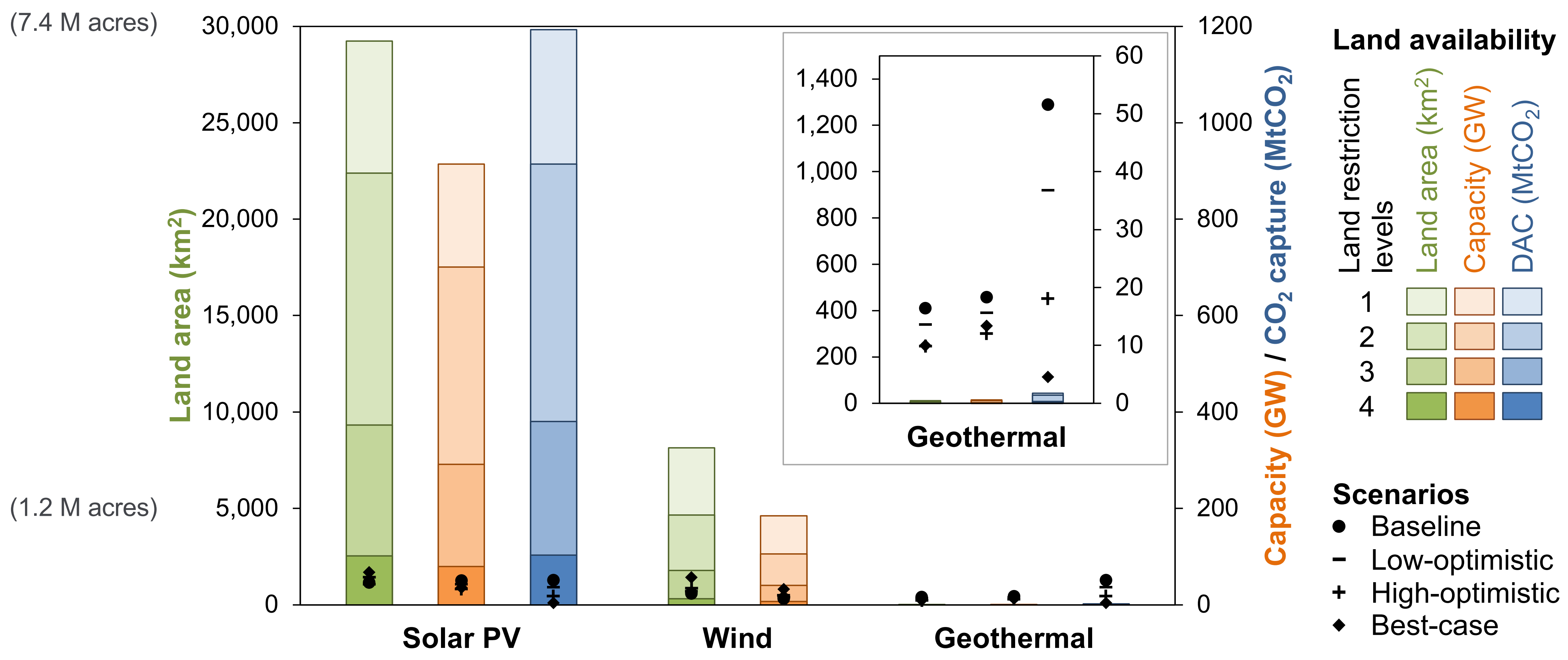
Land area for utilities and DAC in 2050

Additional electricity generation needed for utilities in 2050: +157-227% compared to 2020



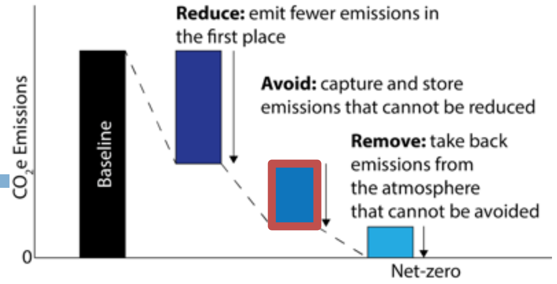
Land area for utilities and DAC in 2050

All electricity generation and DAC projects could be developed while preserving the environment.



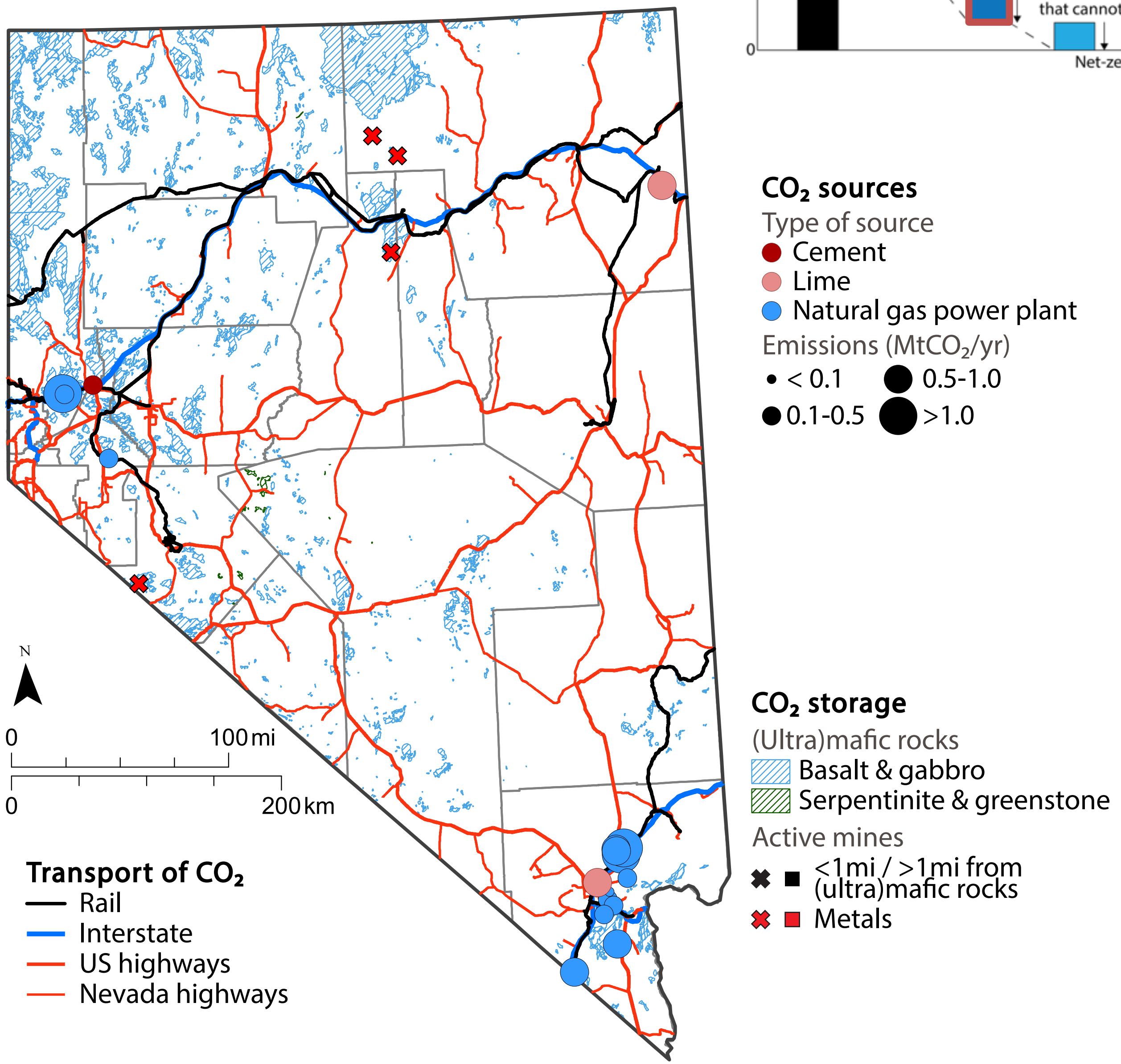
Land restriction levels from the "Power of Place" study indicates areas that would comply with (1) legal protections, (2) and administrative protections, (3) and high conservation value preservation, (4) and landscape intactness preservation.

Avoiding CO_2 emissions



Avoiding CO_2 emissions
=
Point source carbon capture
+
Carbon storage

Transportation of CO_2 or alkaline feedstocks



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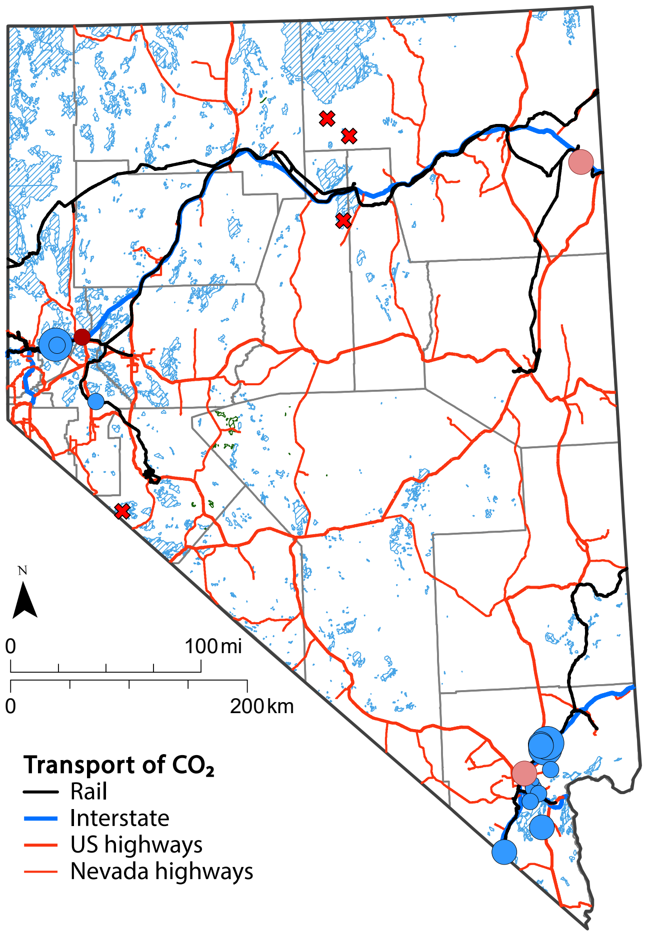
Understanding regional trends and opportunities



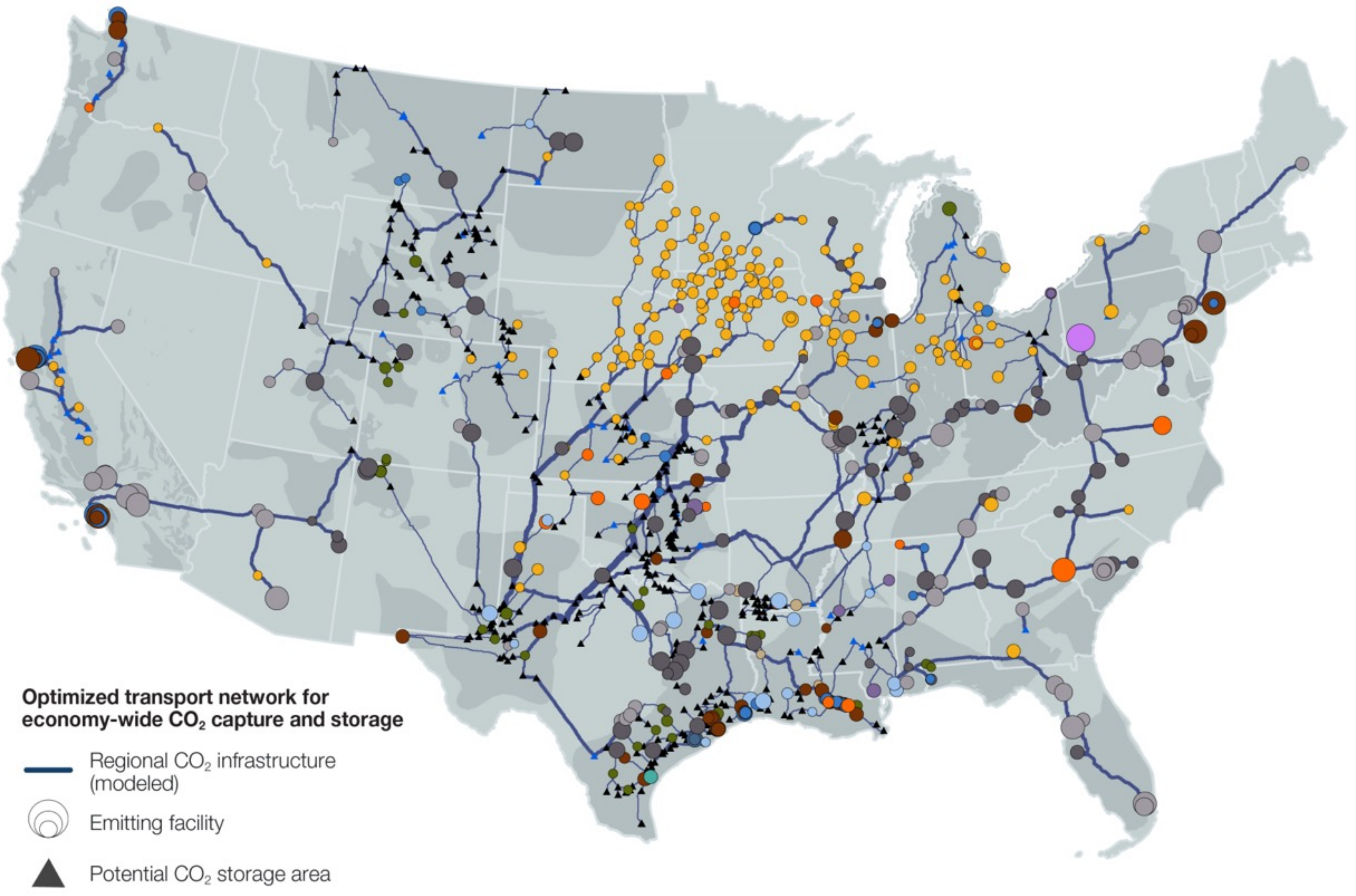


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Figure authored by GPI based on results from the SimCCS model, 2020.

Procedural recommendations

- assess (lifecycle assessments) and communicate (robust materials)
- developers: conduct SIA and EIA prior to site selection
- engage communities early in the planning process
- establish agreements to confer an equitable distribution of benefits to communities where CDR is to be sited

Policy recommendations

- IIJA = 3.5B in DAC hubs
- DOE Carbon Negative Shot = all CDR → $100/tCO_2$
- IRA = boosts to 45Q, increased incentives for energy communities
- Justice40 = 40% of benefits flow to disadvantaged communities

- Encourage community engagements and agreements
- Establish job training programs and standards for high-quality employment
- Continue to support advanced RD&D
- Increase support for monitoring, reporting and verification (MRV)


The road to net-zero is paved
with hard problems

Contributors and collaborators

CECLab:
Jen Wilcox
Hélène Pilorgé
Katherine Van Gomes
Daniel Nothaft
Maxwell Pisciotta
Shelvey Swett
Haarini Ramesh
Caroline Magdolen
Jacob Sheldon
Emma Li
Sara Takenaka
Corbyn Stosich
Anna Hallac
Caleb Woodall
Noah McQueen
Sam Layding

TNC Nevada:
Jaina Moan
John Zablocki
Peter Gower
Tanya Anderson

WRI:
Katie Lebling
Zachary Byrum
Elizabeth Bridgewater
Haley Leslie-Bole
Dan Lashof
Karl Hausker
Angela Anderson
Carrie Dellesky

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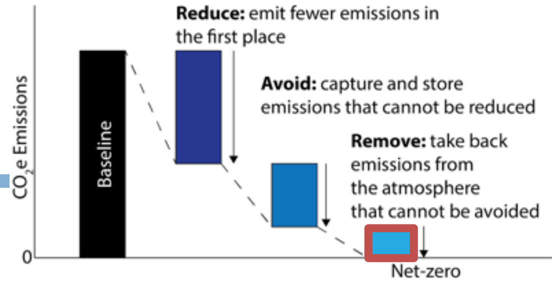
Extra

Removing CO_2 emissions



Carbon dioxide removal (CDR)

=

Direct air capture (DAC)

+

Carbon storage

Siting of DAC

- Low-carbon renewable energy (thermal and/or electric)
- CO_2 storage or transportation infrastructure
- Critical habitats preservation
- Environmental justice considerations

Land restriction levels from the "Power of Place" study indicates areas that would comply with
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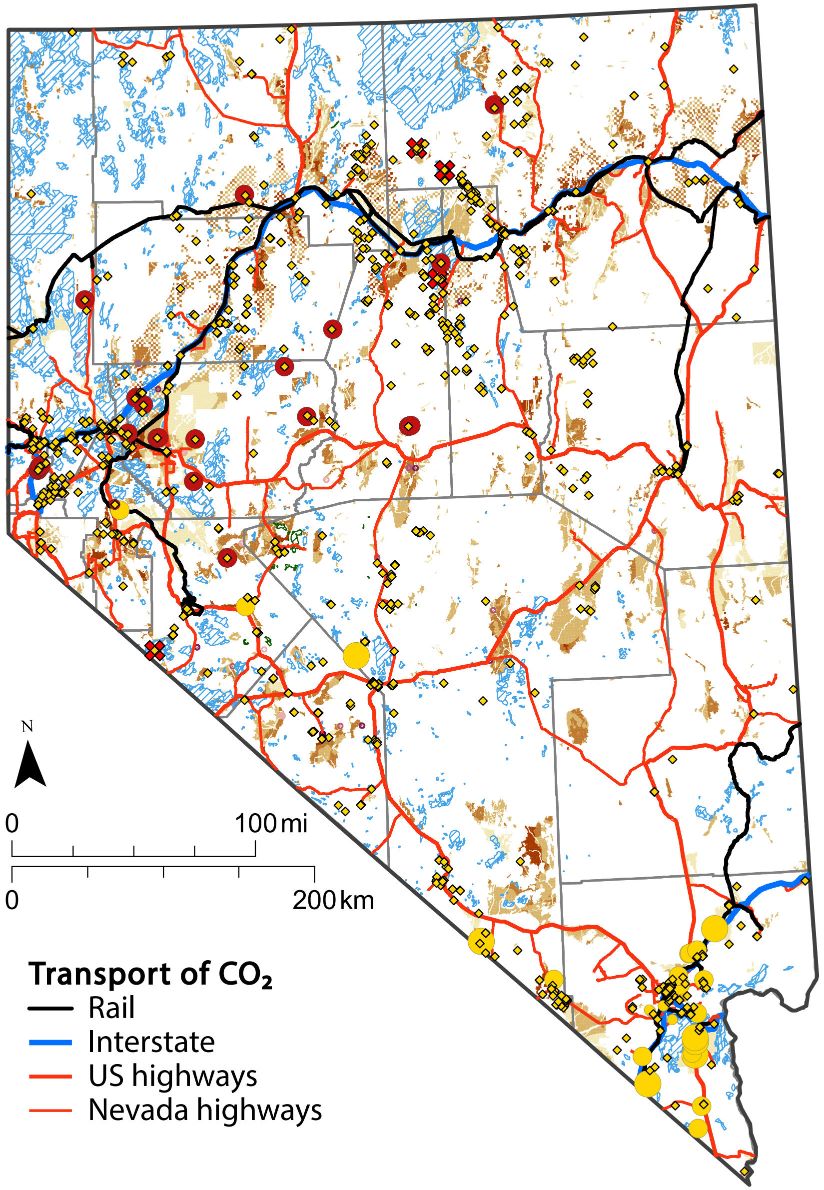


Transport of CO_2
- Rail
- Interstate
- US highways
- Nevada highways

Energy

Operating power plants
- Solar
- Geothermal

Capacity of power plants (MW)
- <10
- 10-100
- 100-1,000

"Mining the Sun" study
- Solar

"Power of Place" study

Environmental restriction level

	1	2	3	4
Solar				
Geothermal				
Environmental impact	+++	++	+	-

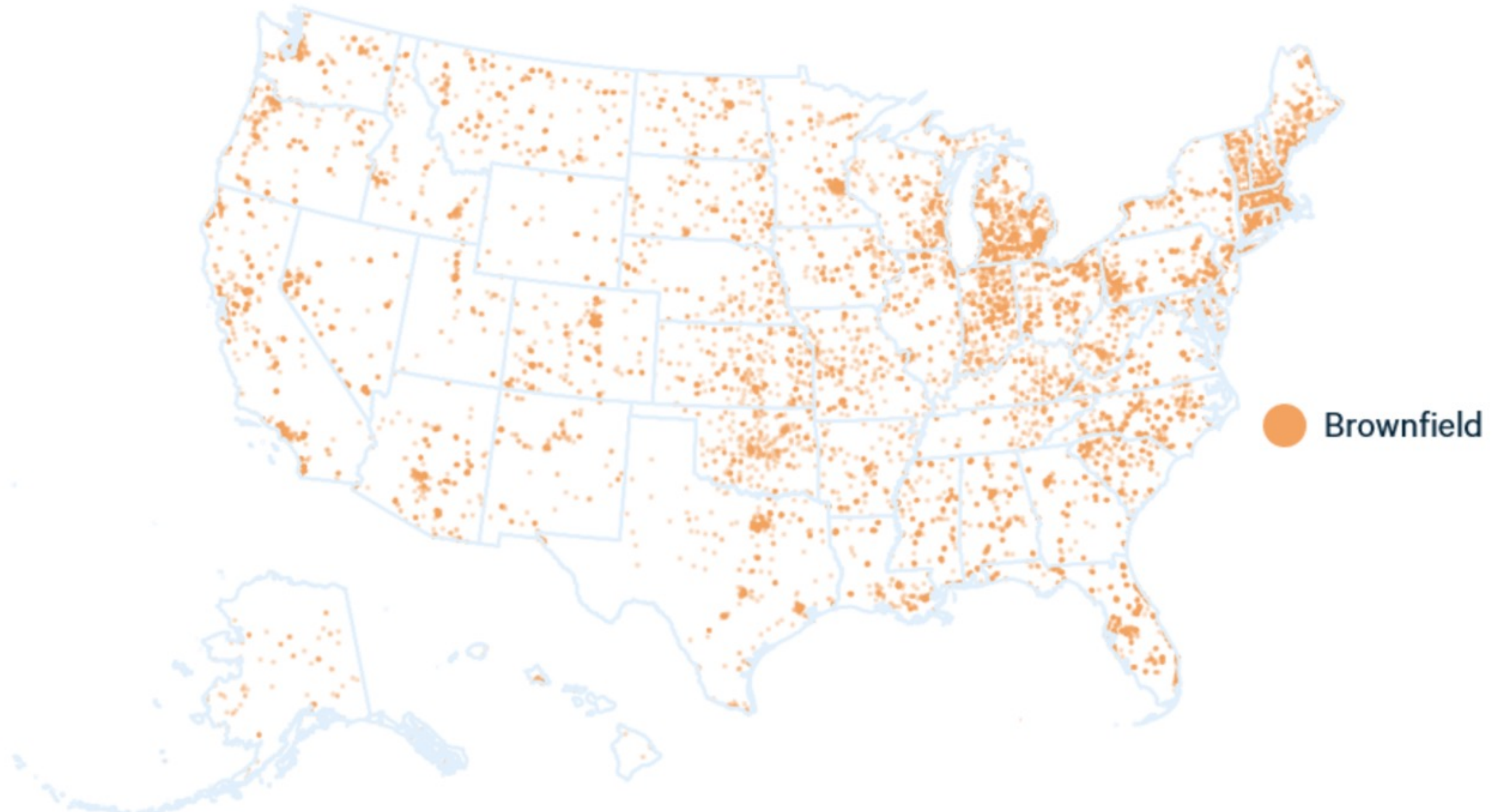
CO_2 storage

(Ultra)mafic rocks
- Basalt & gabbro
- Serpentinite & greenstone

Active mines
- <1mi / >1mi from (ultra)mafic rocks
- Metals

Brownfields

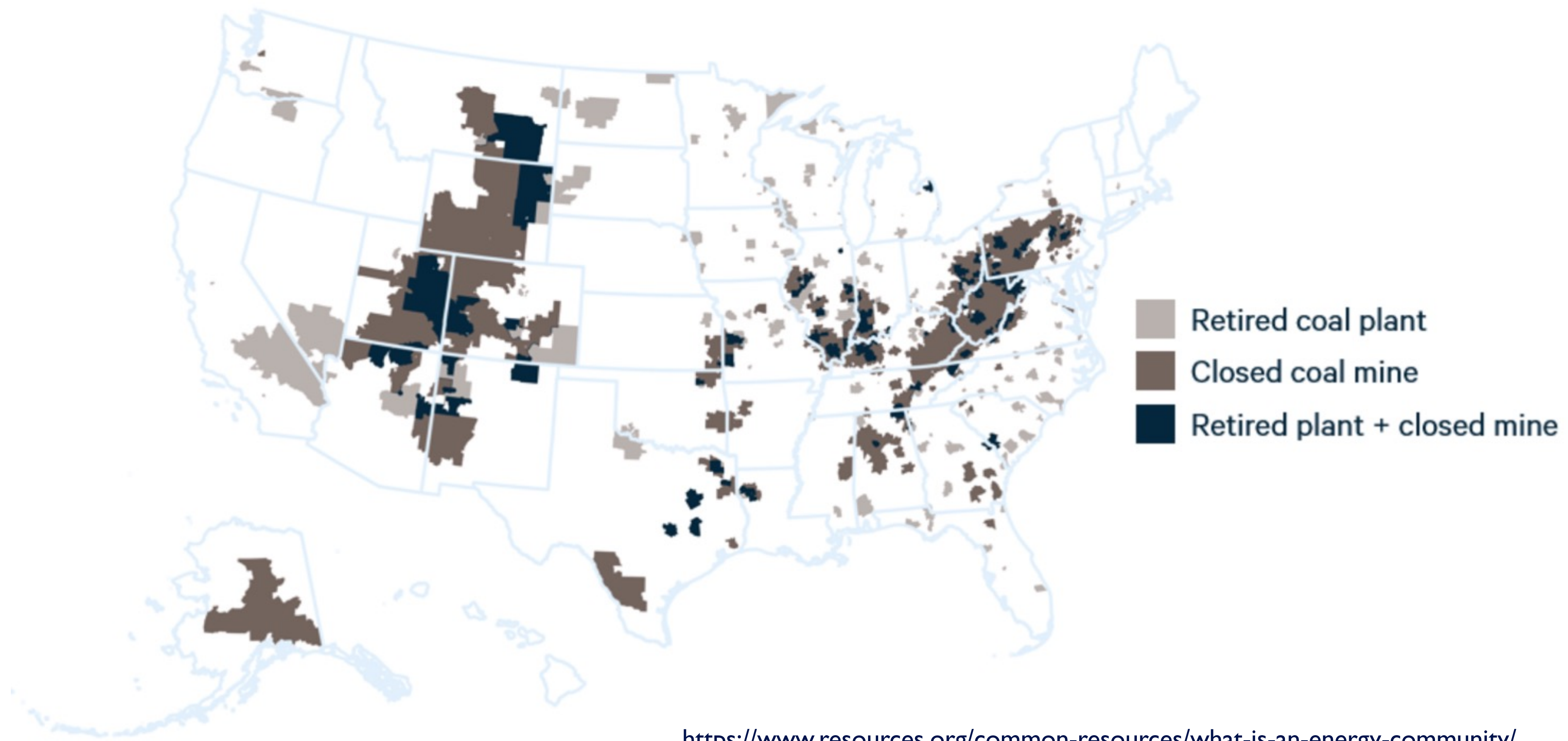
Small parcels of pollution-contaminated land which, after designation as such by EPA, can receive funding for cleanup, reclamation.



https://www.resources.org/common-resources/what-is-an-energy-community/

Coal communities

Any census tract where a coal-fired power plant has closed since 2010, or a coal mine has closed since 2000.



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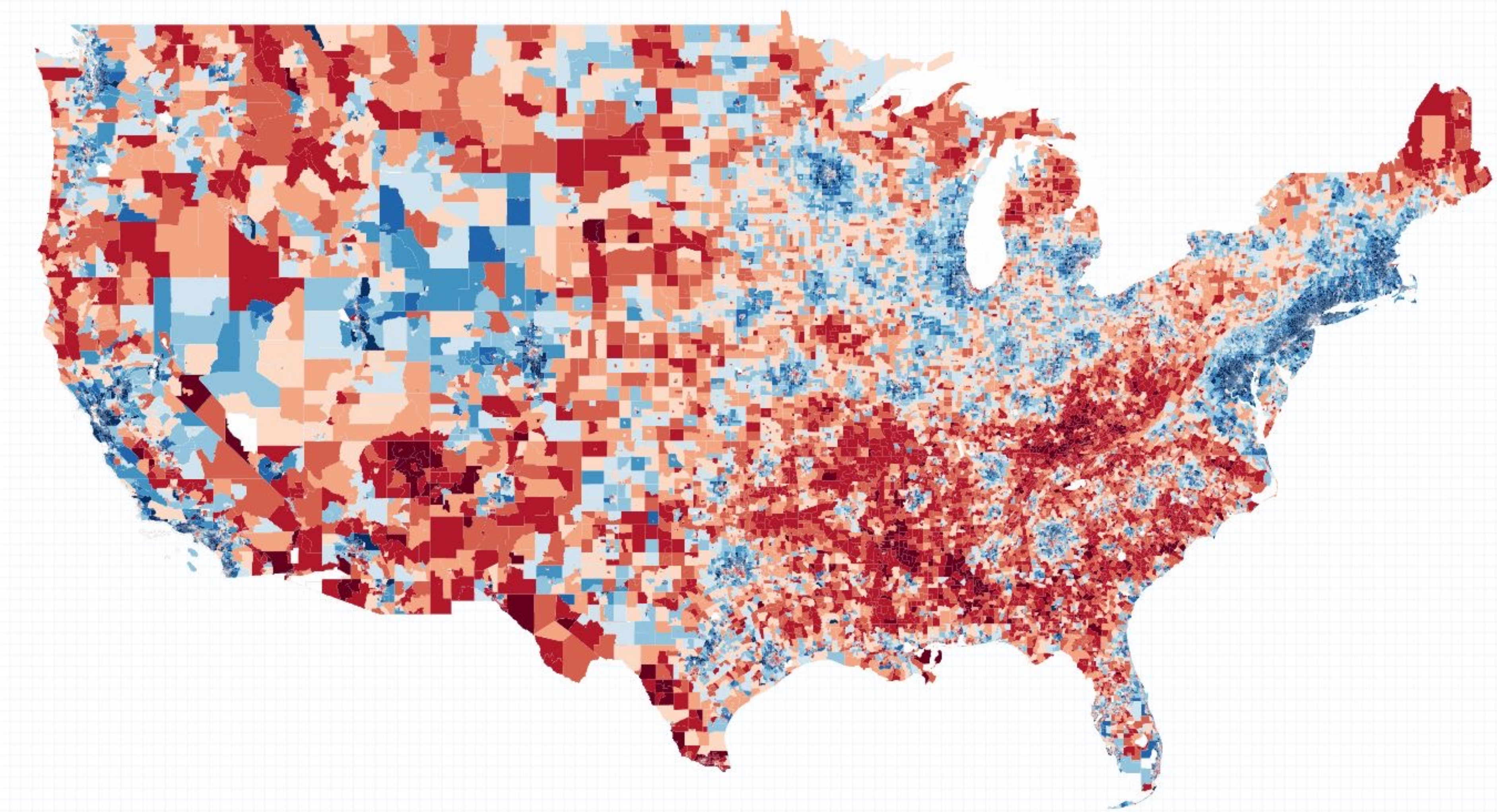
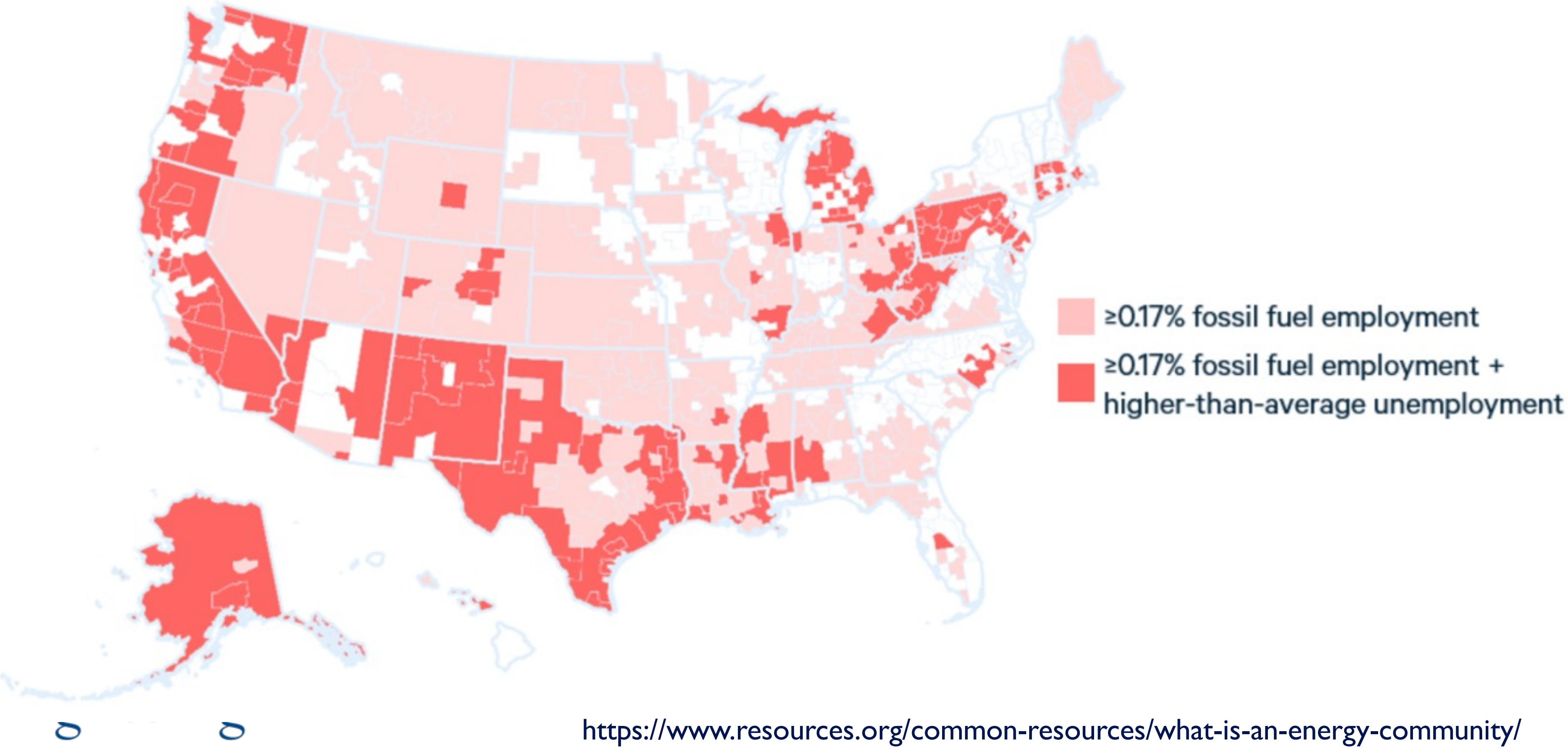


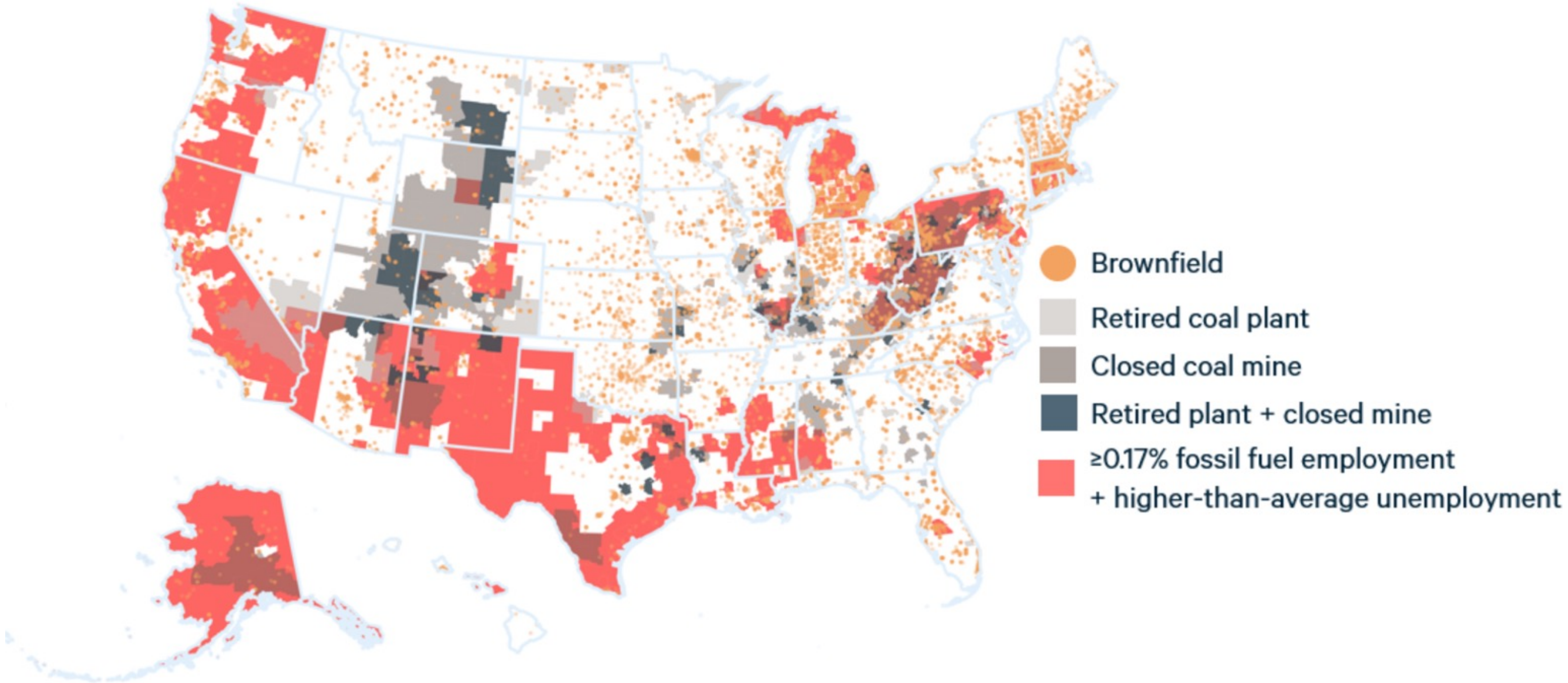
Jobs and tax revenue

Area where **0.17%** or greater direct employment or at least 25% of local tax revenues [are] related to extraction, processing, transport, or storage of coal, oil, or natural gas"
AND
" employment is **at or above the national average** in the previous year". (5.3% in 2021)



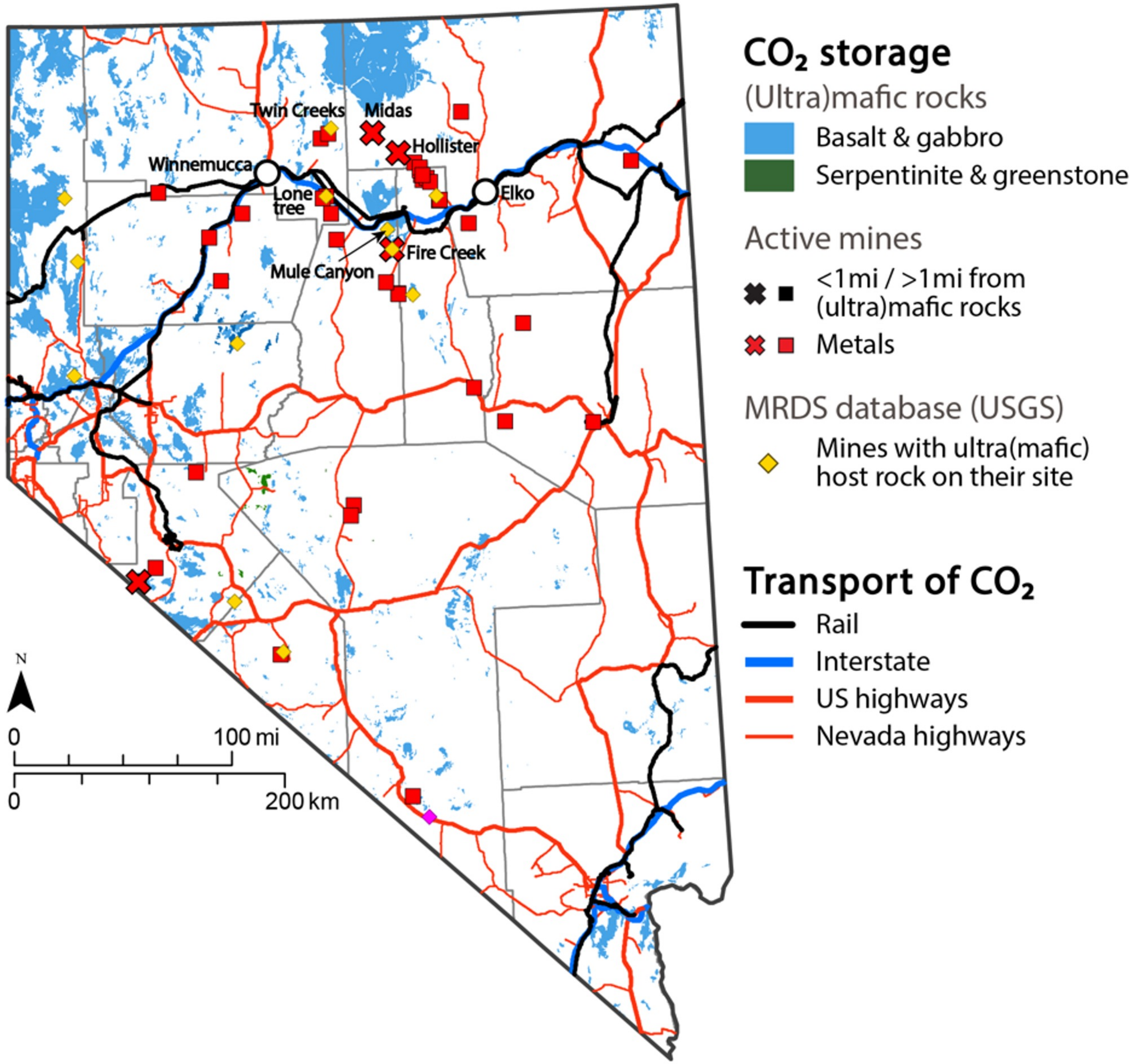
https://www.resources.org/common-resources/what-is-an-energy-community/

Combined coverage



https://www.resources.org/common-resources/what-is-an-energy-community/

Storage potential in Nevada



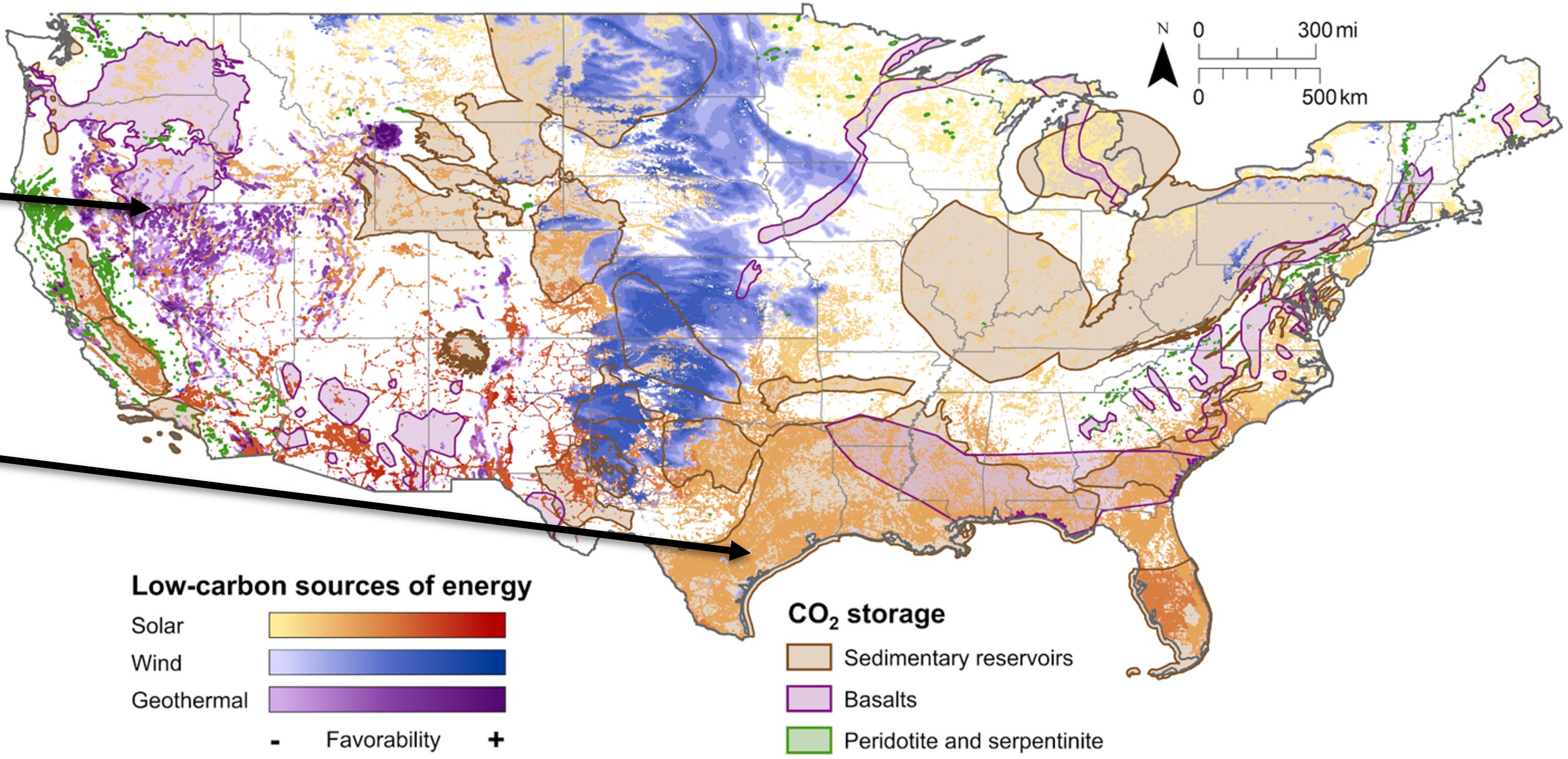
- Basalts are not deep enough for in-situ CO_2 injection
- Large amounts of mine tailings
  - Limited amount of mine tailings with alkalinity
  - Most of the mine tailings seem to be made of gypsum
- CO_2 captured in Nevada will likely need to be transported for storage elsewhere, unless
  - We find suitable sedimentary formations
  - Gypsum can be used in the carbon mineralization process

A purely techno-economic approach shows DAC plant placement close to low-carbon energy and reliable storage sites

We might place DAC **here** to take advantage of low carbon thermal energy,

or **here** to take advantage of nearby storage opportunities,

BUT ...



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