CCS and the net zero economy
National infrastructure, carbon deserts, and regional storage hubs

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CARBON SOLUTIONS LLC

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CARBON SOLUTIONS LLC

Mission-driven small business

- *CARBON SOLUTIONS works with industry, government, non-profits, researchers, & other stakeholders to identify & implement real-world solutions for low-carbon energy challenges.*

History

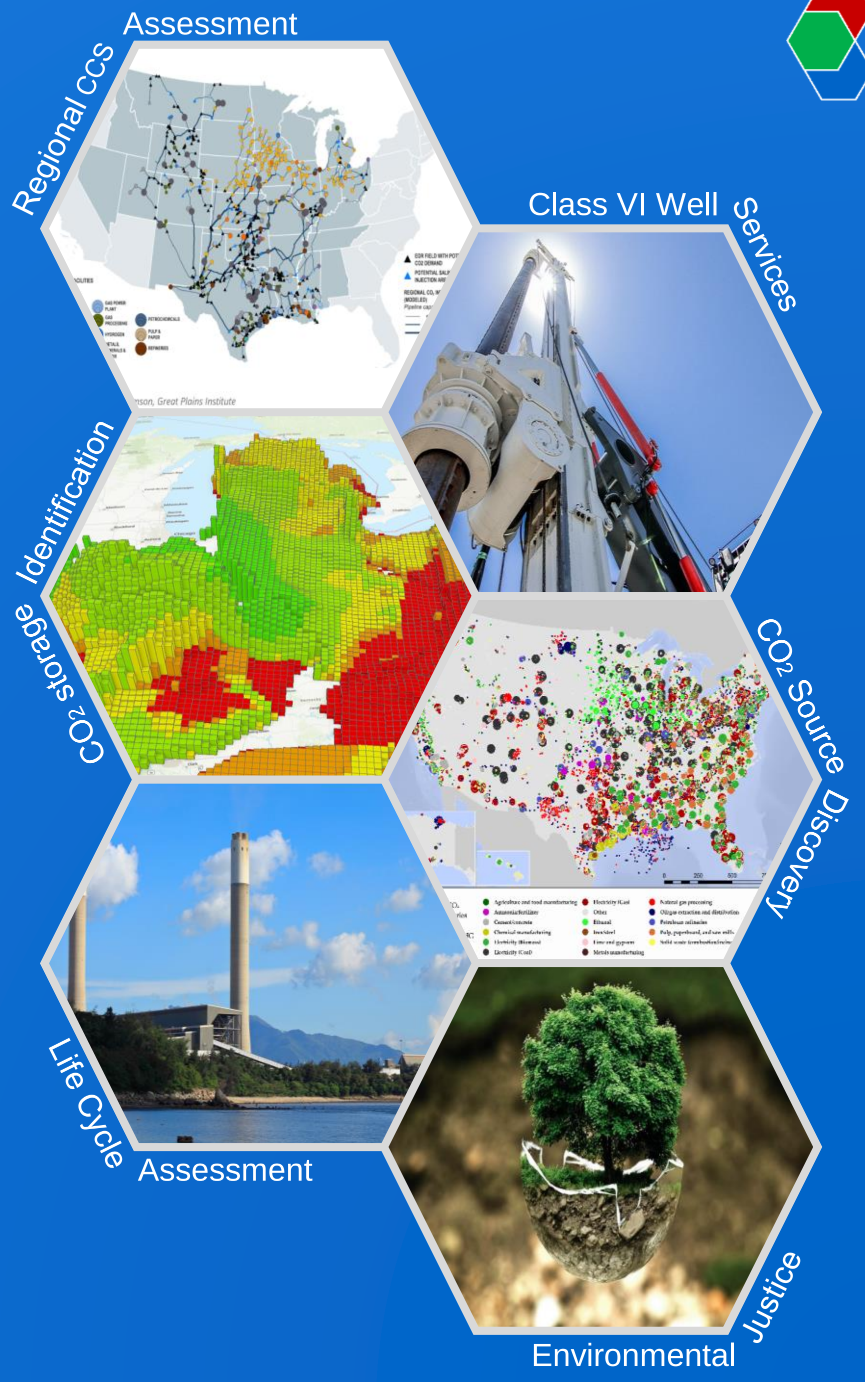
- Launched 2021 | 30 employees | 50+ projects.
- Research | Consulting & Services | Software Development
- **FUNDING:** 60% Fed. | 25% NGOs | 15% Industry.

Energy applications

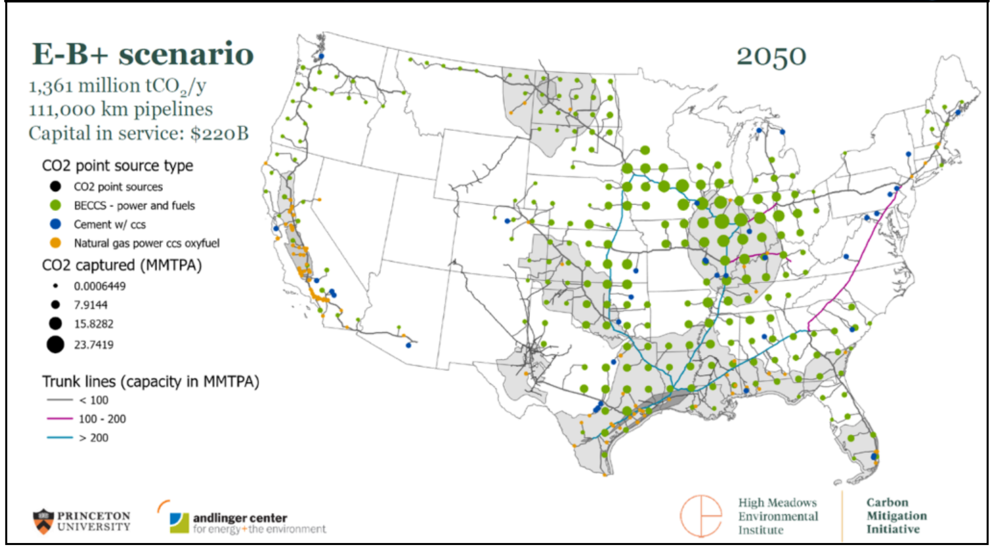
- CCS, hydrogen, direct air capture, geothermal, wind, energy storage, grid modeling, electric vehicles, energy equity…

Data analytics

- Optimization, reservoir simulation, ML/AI, LCA, TEA, econometrics, GIScience…



Net Zero Economies & CCS



Princeton Net Zero America: https://netzeroamerica.princeton.edu

LCR Net Zero 2050: https://lcri-netzero.epri.com

US net-zero studies

- Gigatonne scale.
- Up to 1.7–2.0 $GtCO_2$/yr.
- 1,000s of sources.
- >100,000 km of pipeline.
- 1,000s of wells/sites.
- 100-fold expansion.

CCS scale challenge

1. National infrastructure.
2. Carbon deserts.
3. Regional storage hubs.

Three studies

1. Decarbonize US fossil electricity.
2. Decarbonize US industrial sectors.
3. Mid-Atlantic industries & offshore storage

Integrated CCS assessment

- Simultaneously understand CO_2 capture, transport, & storage.

CO_2 Capture

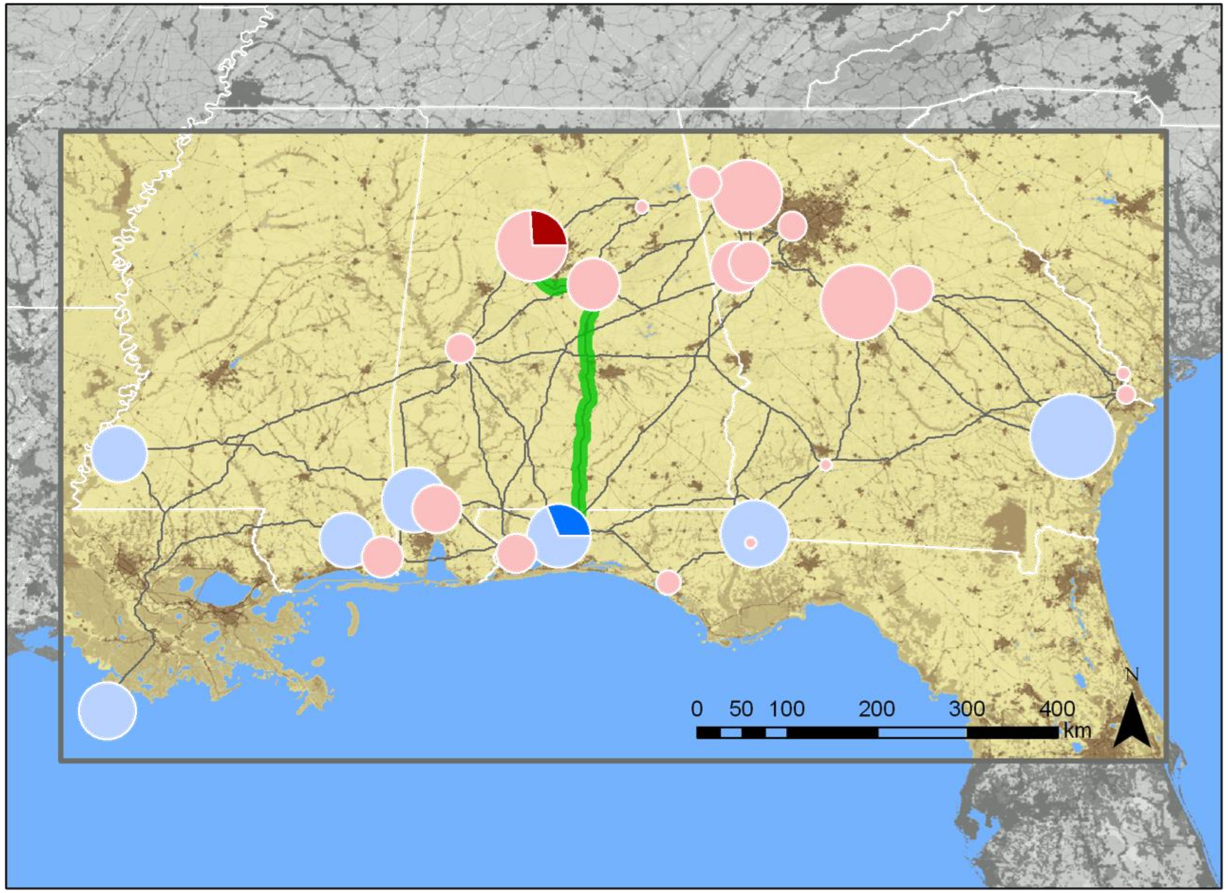
- Emissions, capturable CO_2, purity by multiple streams, economics over space & time.

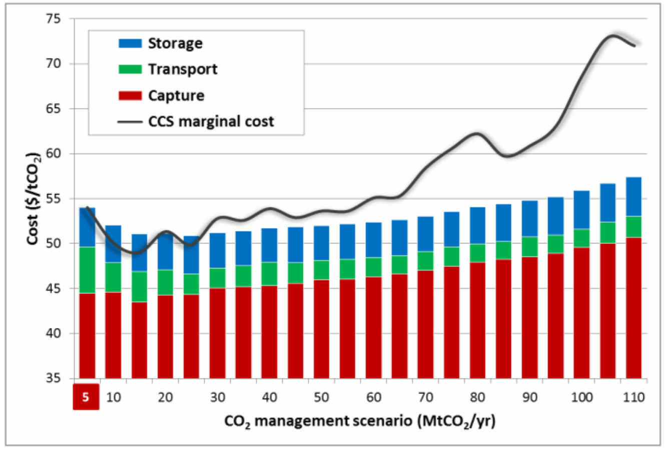
CO_2 Transport

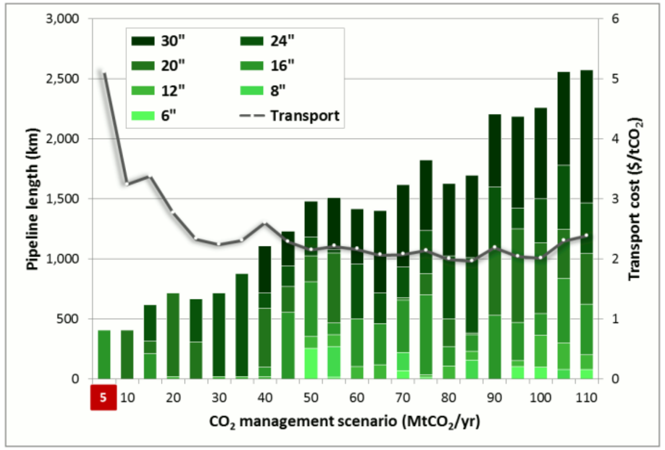
- **ROUTES:** Potential routes considering multi-dimensional geographies.
- **PIPELINES:** Capacities, trunklines to aggregate CO_2, economics (capital, fixed & variable O&M).

CO_2 Storage:

- **STORAGE:** Identify ideal sites, dynamic CO_2 injection & storage, lifetime reservoir costs (injection, storage, & PISC).
- **UTILIZATION:** Oil, shale gas, geothermal, & materials.

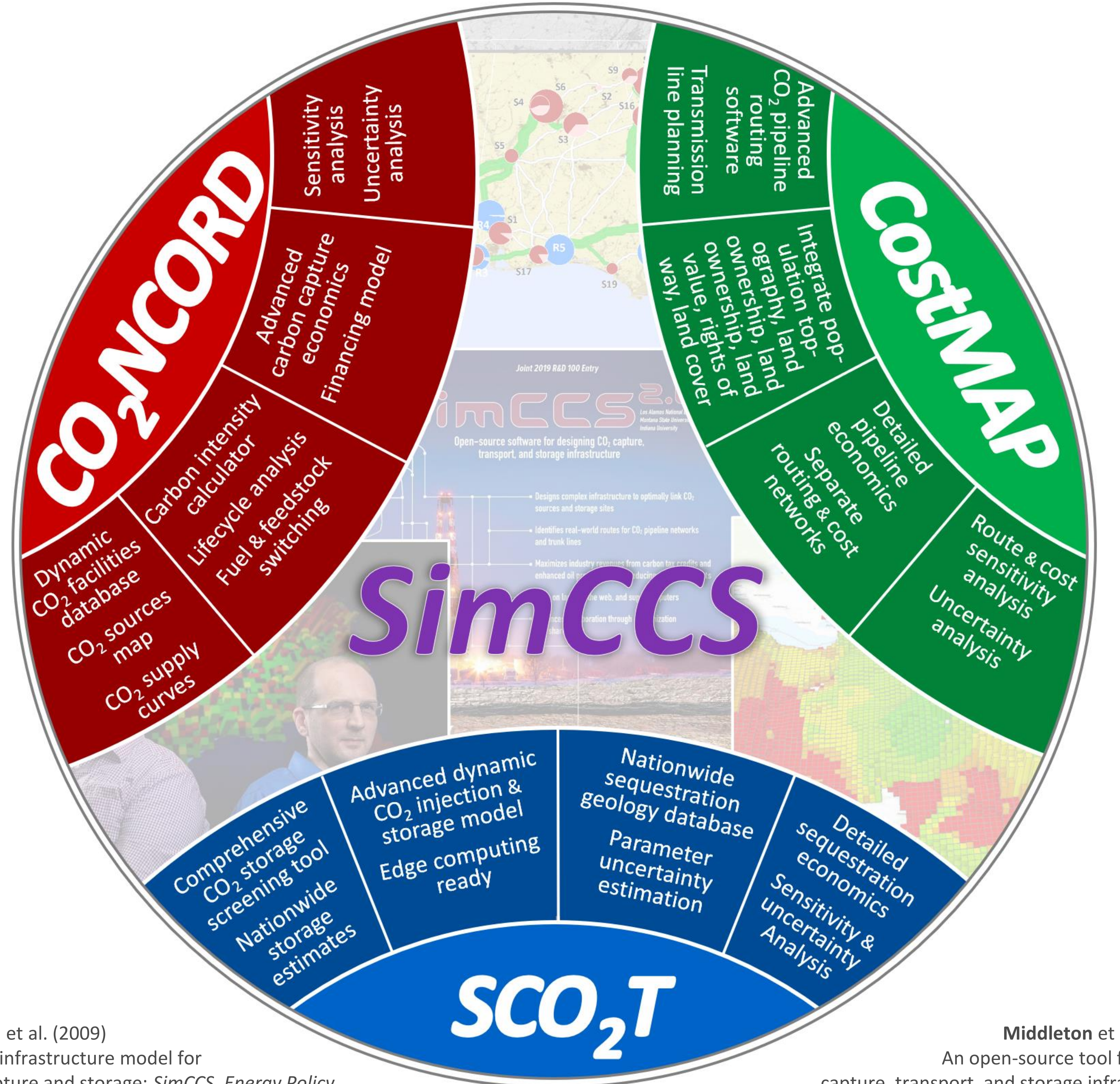






Middleton et al. (2012) The cross-scale science of CO_2 capture and storage: from pore scale to regional scale, *E&ES*.`

SimCCS^PRO Software



Middleton et al. (2009)
A scalable infrastructure model for carbon capture and storage: *SimCCS*, *Energy Policy*.

Middleton et al. (2020) *SimCCS*: An open-source tool for optimizing CO_2 capture, transport, and storage infrastructure, *EM&S*.

SimCCS^PRO | ANALYSIS

- Decision support across the CCS value chain.

CO_2NCORD | CAPTURE

- Dynamic, customizable CO_2 capture database.

CostMAP^PRO | TRANSPORT

- Multiscale, multi-attribute pipeline routing.

SCO_2T^PRO | STORAGE

- Advanced tool for dynamic CO_2 storage & costs.

https://www.carbonsolutionsllc.com/software

CO_2NCORD

Why?

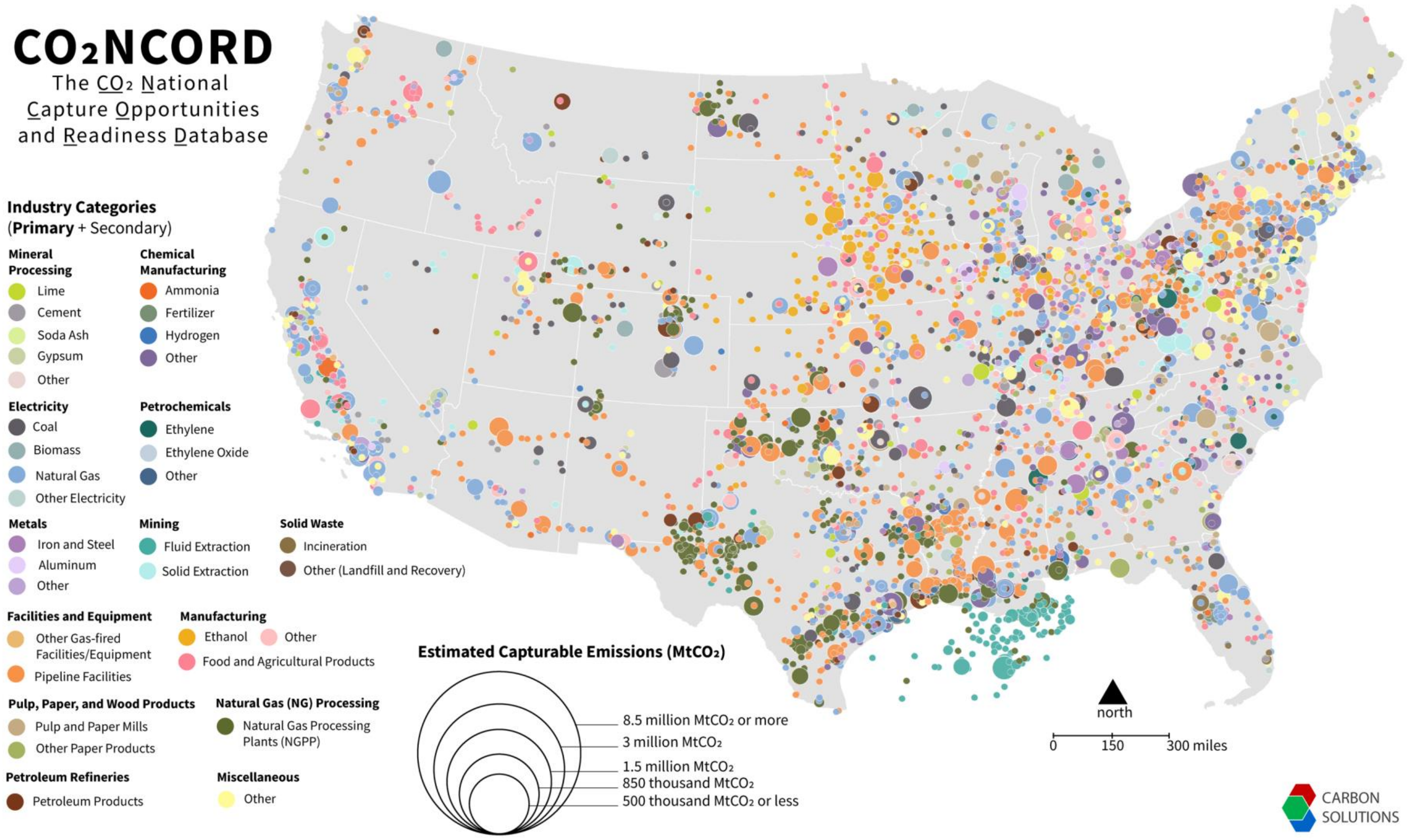
- Commercial-scale CO_2 capture opportunities.

How?

- **FUSE:** emissions data from EPA GHGRP/FLIGHT, EPA eGRID, RFA (ethanol)…
- **Fuse:** capture cost & stream data from 15+ lit. sources.
- **EXPERTISE:** industry-leading experience with CO_2 capture.

What?

- **GEODATABASE:** source locations, CO_2 streams (quantity & purity), & capture costs.
- **SUPPLY CURVES:** Identify economic opportunities.
- Market Assessment.



CARBON SOLUTIONS – NSF-SBIR (2023) A Decision-Support Tool for Identifying Carbon Dioxide (CO_2) Capture Opportunities for the Nation's Energy Transition.

CostMAP^PRO

Why?

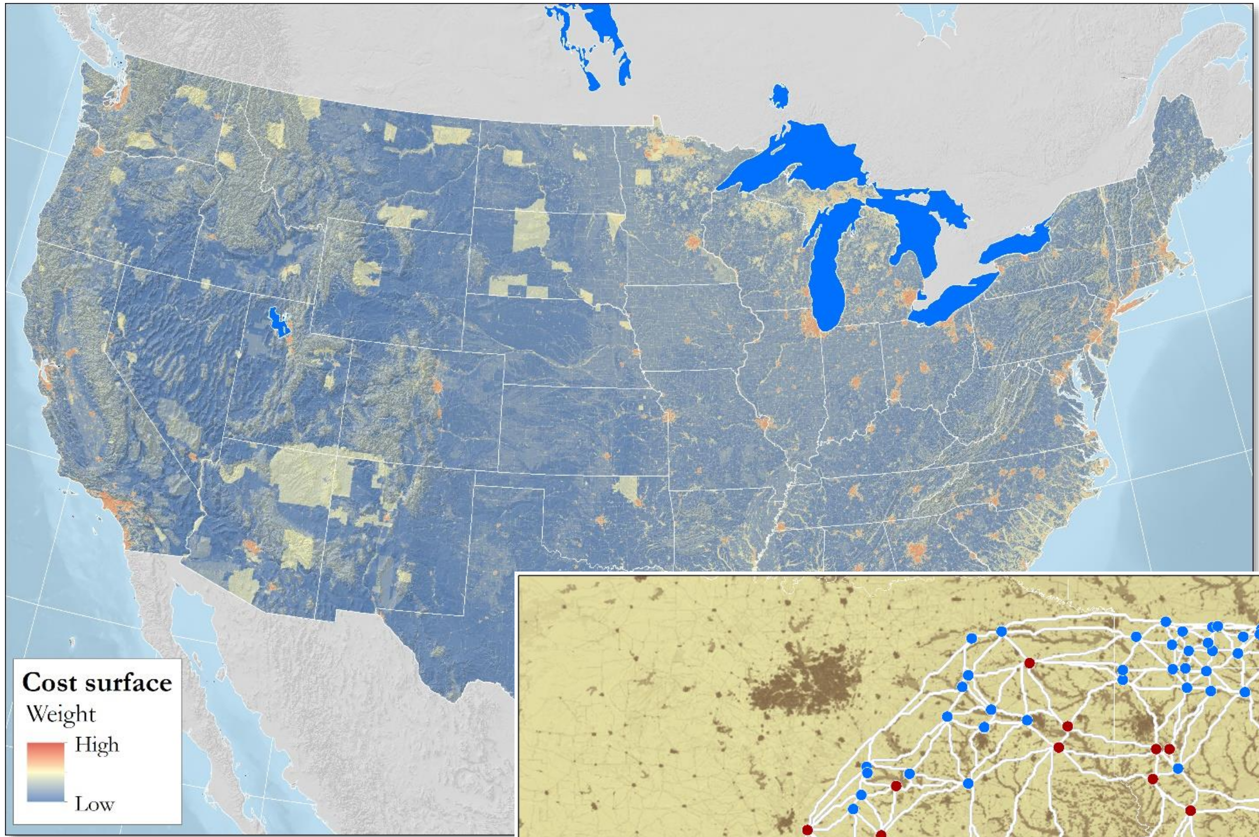
- Understand where, how, & cost of CO_2 transportation.

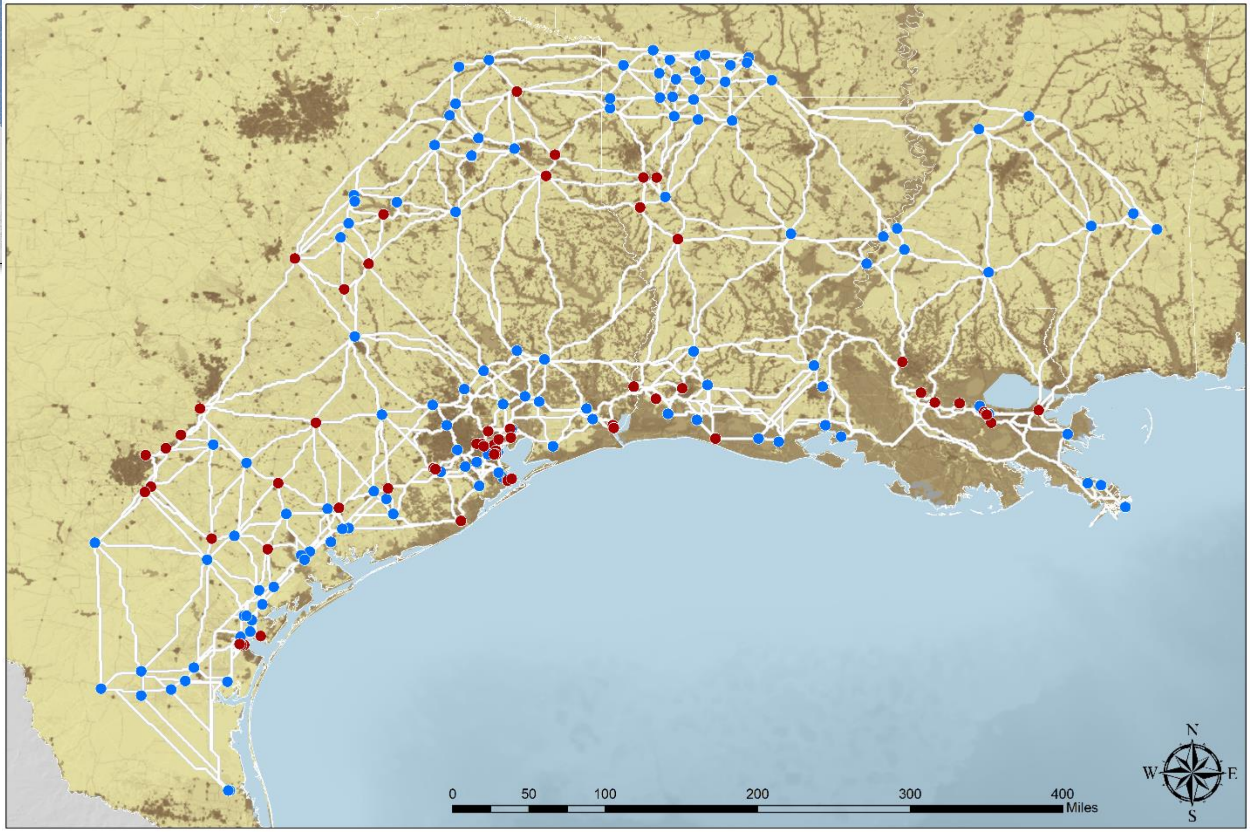
How?

- Nonlinear integration of ROWs (e.g., pipelines), barriers (e.g., rivers), population, topography, land use, ownership, environmental justice…
- *SimCCS* cost model.

What?

- Next-generation software for pipeline costs & routing.
- Cost & routing surfaces, grid cells 10 m to ~1,000 m.
- Multiple pipeline routes, avoid sensitive areas.
- Pipeline route robustness.





Middleton et al. (2012) Generating candidate networks for optimization: The CO_2 capture and storage optimization problem, *Computers, Environment and Urban Systems.*

Hoover et al. (2020) *CostMAP*: an open-source software package for developing cost surfaces using a multi-scale search kernel, *International Journal of Geographical Information Science.*

SCO_2T^{PRO}

Why?

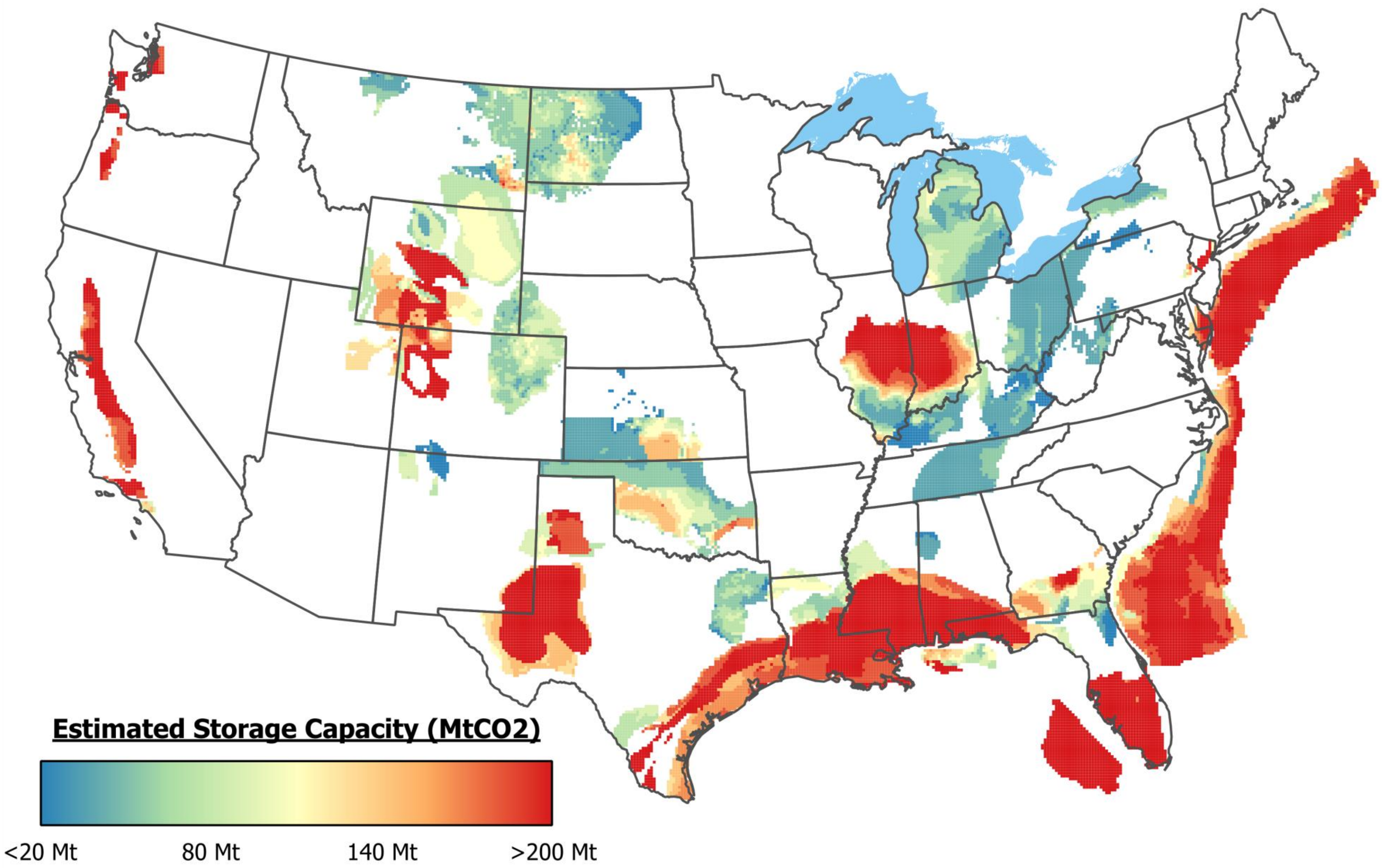
- Rapidly calculate realistic injection, storage & costs.

How?

- Machine learning for CO_2 sequestration that connects dynamic CO_2 injection & storage with economics.
- Best US-wide sequestration geology.

What?

- Tool to rapidly calculate dynamic CO_2 injection, storage & costs (1000s of realizations per second).
- Regional storage screening.



Middleton et al. (2020) Great SCO_2T! Rapid tool for carbon sequestration science, engineering, and economics, *Applied Computing and Geosciences*.

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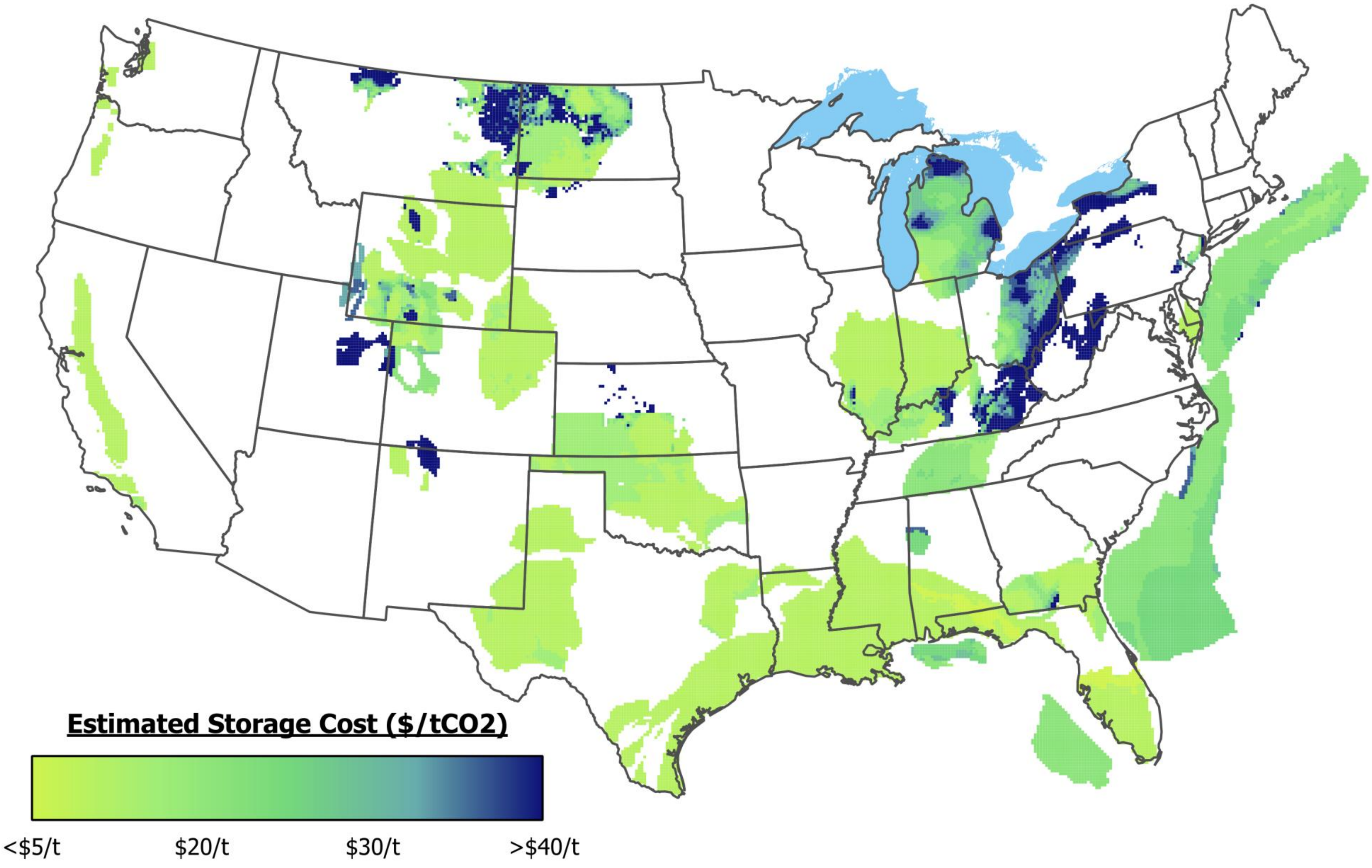


Middleton et al. (2020) Great *SCO_2T*! Rapid tool for carbon sequestration science, engineering, and economics, *Applied Computing and Geosciences*.

STUDY 1

Decarbonize post-2030 fossil power

Study Design

Source parameters

- **Fuels:** All coals, NG.
- **Min capture:** 0.5 $MtCO_2$/yr.
- **Capture rate:** 90%.
- **Retirements:** 2030.
- **Capacity factor:** 30%.

Sources

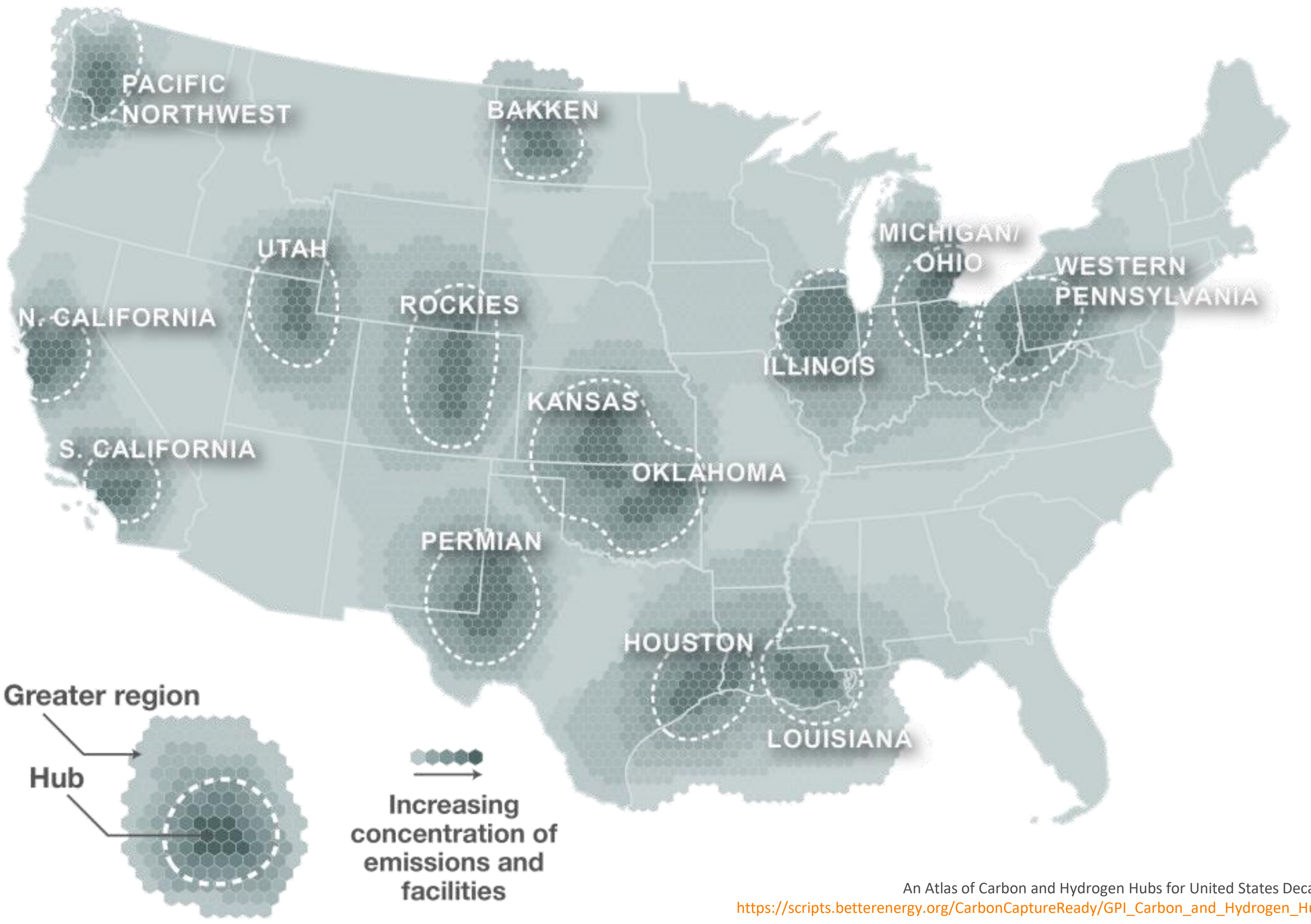
- 429 plants | 1,044 $MtCO_2$/yr.
- 136 coal | 600 $MtCO_2$/yr.
- 293 NGCC | 444 $MtCO_2$/yr.

Storage

- Saline, onshore only.
- 14 hubs, 371 SCO_2T sites.

Scenario

- Capture 200|400|600|800|1,000|1,044 $MtCO_2$/yr.



An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization : https://scripts.betterenergy.org/CarbonCaptureReady/GPI_Carbon_and_Hydrogen_Hubs_Atlas.pdf

Result: 1,044 $MtCO_2$/yr

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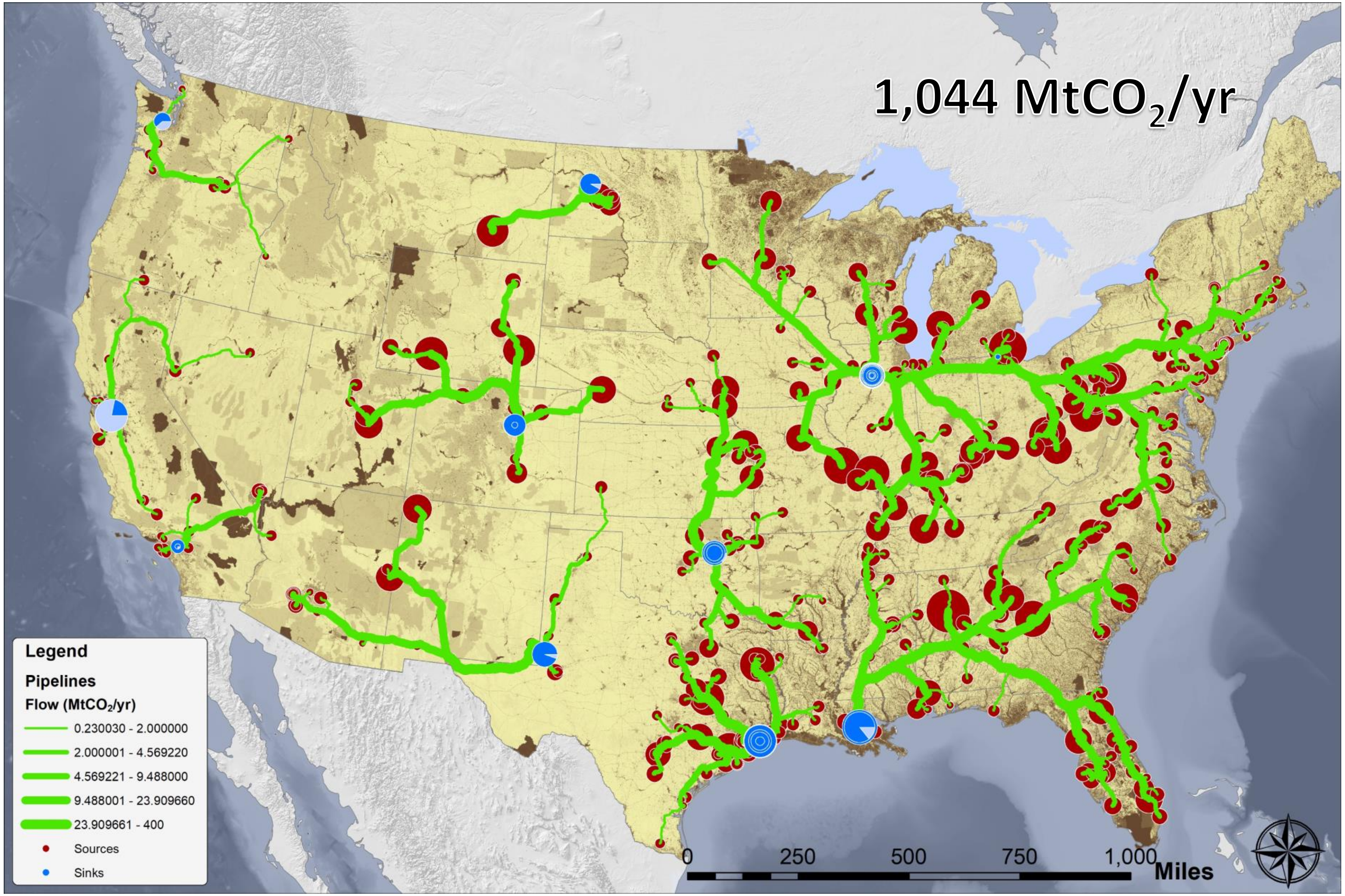


Distributed vs. Centralized Storage

Distributed Scenarios

Target ($MtCO_2$/yr)	# Sources	# Sinks	# Hubs	Network Length (km)	Total Cost ($/t$CO_2$)				Marginal Cost ($/t$CO_2$)			
					Total	Capture	Transport	Storage	Total	Capture	Transport	Storage
200	43	32	-	2,133	79.22	68.30	2.24	8.68	79.22	68.30	2.24	8.68
400	102	64	-	5,147	80.97	69.02	3.18	8.76	82.71	69.75	4.12	8.84
600	183	96	-	9,627	82.23	69.60	4.08	8.55	84.76	70.75	5.88	8.12
800	260	120	-	16,064	83.63	69.78	5.28	8.57	87.84	70.31	8.89	8.64
1,000	389	142	-	27,814	85.99	70.26	7.15	8.58	95.41	72.20	14.60	8.61
1,044	429	146	-	32,550	86.92	70.37	8.04	8.52	108.06	72.74	28.26	7.05

Centralized Scenarios

Target ($MtCO_2$/yr)	# Sources	# Sinks	# Hubs	Network Length (km)	Total Cost ($/t$CO_2$)				Marginal Cost ($/t$CO_2$)			
					Total	Capture	Transport	Storage	Total	Capture	Transport	Storage
200	66	14	8	4,773	84.27	69.56	6.64	8.07	84.27	69.56	6.64	8.07
400	122	26	12	10,038	85.51	69.30	7.79	8.42	86.75	69.04	8.94	8.77
600	175	29	13	16,458	87.38	69.26	10.02	8.10	91.12	69.17	14.49	7.46
800	266	33	13	24,736	88.72	69.71	10.94	8.07	92.74	71.06	13.70	7.98
1,000	388	38	13	35,291	91.52	70.25	13.20	8.07	102.71	72.41	22.23	8.07
1,044	429	38	13	40,361	92.13	70.37	13.68	8.09	106.15	73.04	24.63	8.49

STUDY 2
All 45Q-eligible industrial facilities

Study Design

Source parameters

- **Sectors:** Ammonia, hydrogen, ethanol, aluminium, iron & steel, cement, lime, natural gas processing, ethylene, petro-chemicals, pulp & paper.
- **Min:** 12,500 tCO_2/yr.

Sources

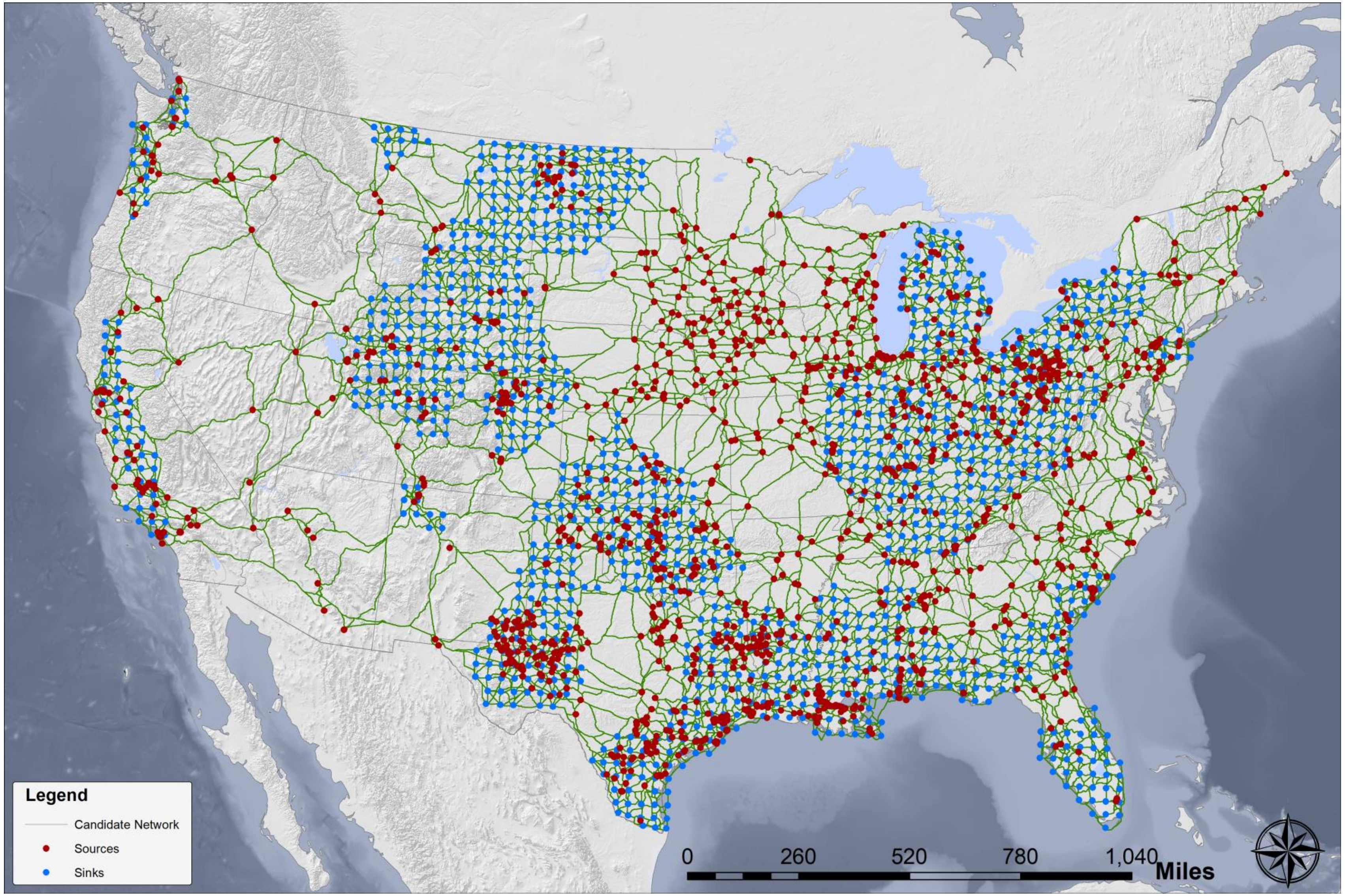
- **All streams**: 2731.
- 532 $MtCO_2$/yr.

Storage

- Saline, onshore only.

Scenario

- **Scenario A:** *SimCCS^{CAP}* (capture all CO_2).
- **Scenario B:** *SimCCS^{PRICE}* (profitable under 45Q).



Scenario A: All CO_2 Captured

Capture target

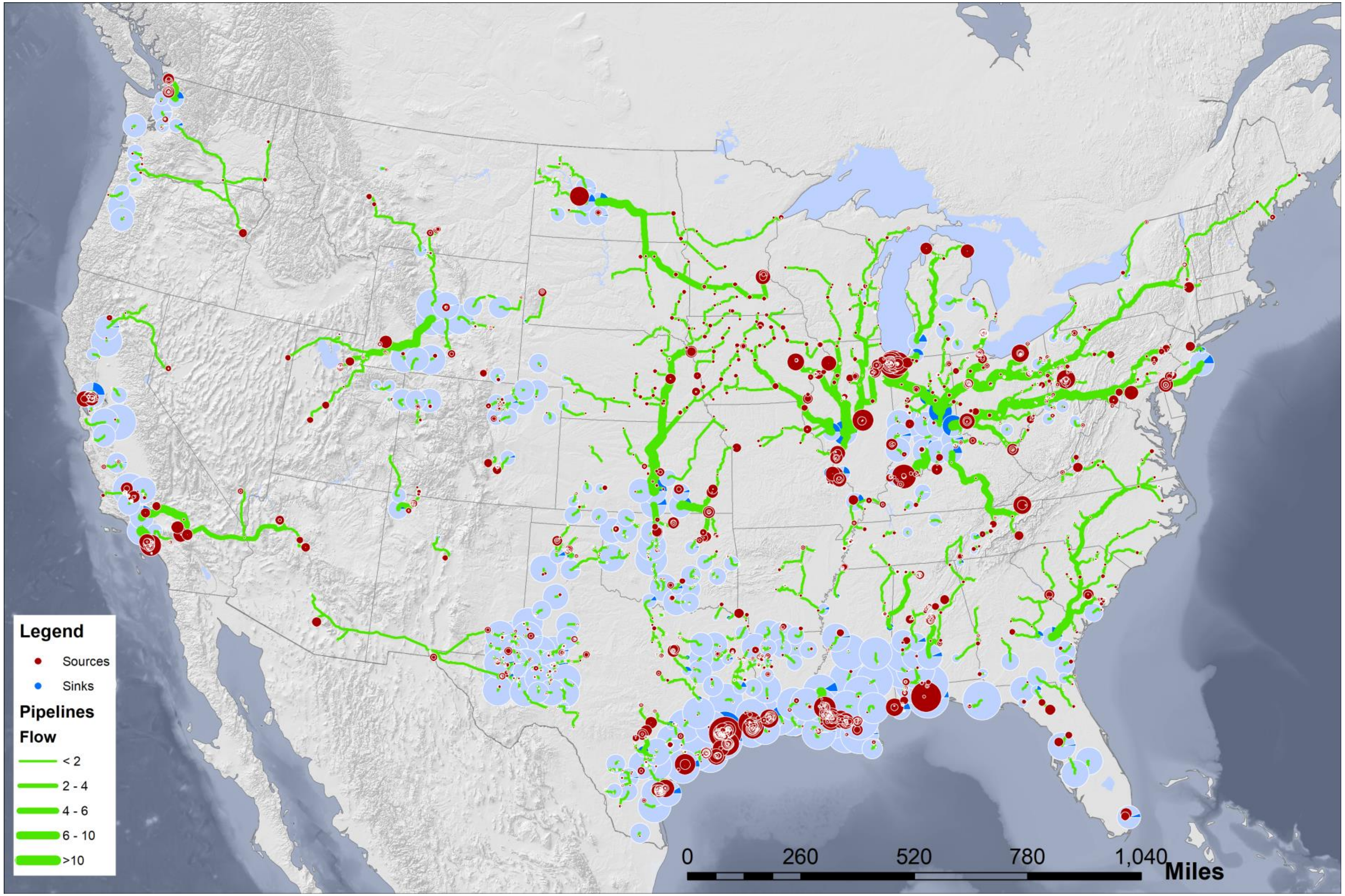
- 532 $MtCO_2$/yr.

Infrastructure

- **Captured:** 532 $MtCO_2$/yr.
- **# sources**: 2731.
- **# sinks:** 329.
- **Network:** 62,703 km.

Costs

- **Capture:** \$65.31/tCO_2.
- **Transport:** \$18.83/tCO_2.
- **Storage:** \$9.23/tCO_2.
- **Total:** \$93.37/tCO_2.



Scenario B: Profitable Under 45Q

Capture target

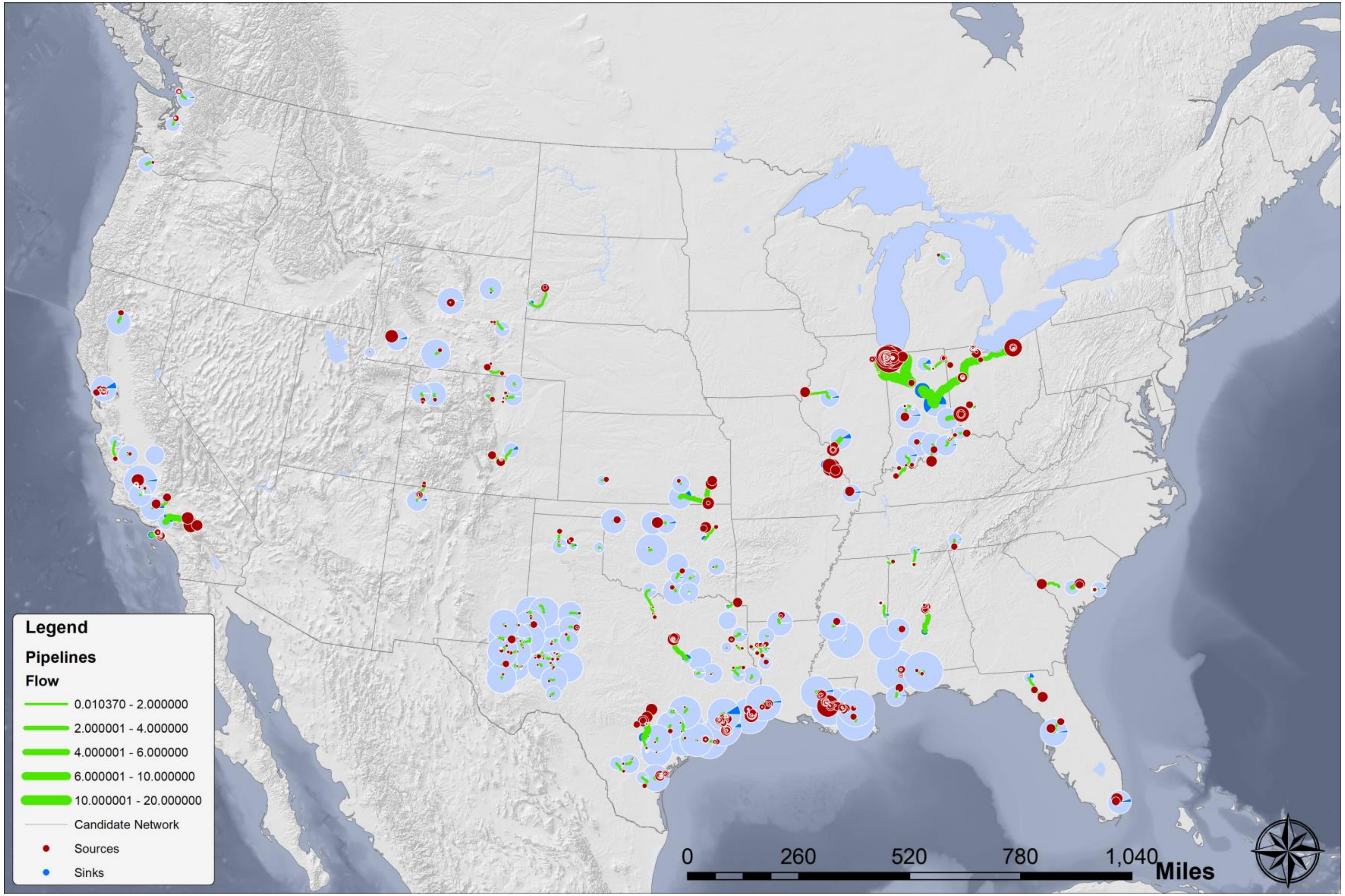
- 45Q: $85/tCO_2$.

Infrastructure

- **Captured:** 176 $MtCO_2$/yr.
- **# sources**: 522 (2731).
- **# sinks:** 143.
- **Network:** 9,317 km.

Costs

- **Capture:** $47.53/$tCO_2$.
- **Transport:** $6.94/$tCO_2$.
- **Storage:** $9.60/$tCO_2$.
- **Total:** -$21.11/$tCO_2$.



STUDY 3
Mid-Atlantic industries
& offshore storage

Offshore Storage

Source parameters

- **Sectors:** Ammonia, hydrogen, ethanol, aluminium, iron & steel, cement, lime, natural gas processing, ethylene, petro-chemicals, pulp & paper.
- **Min:** 12,500 tCO_2/yr.

Sources

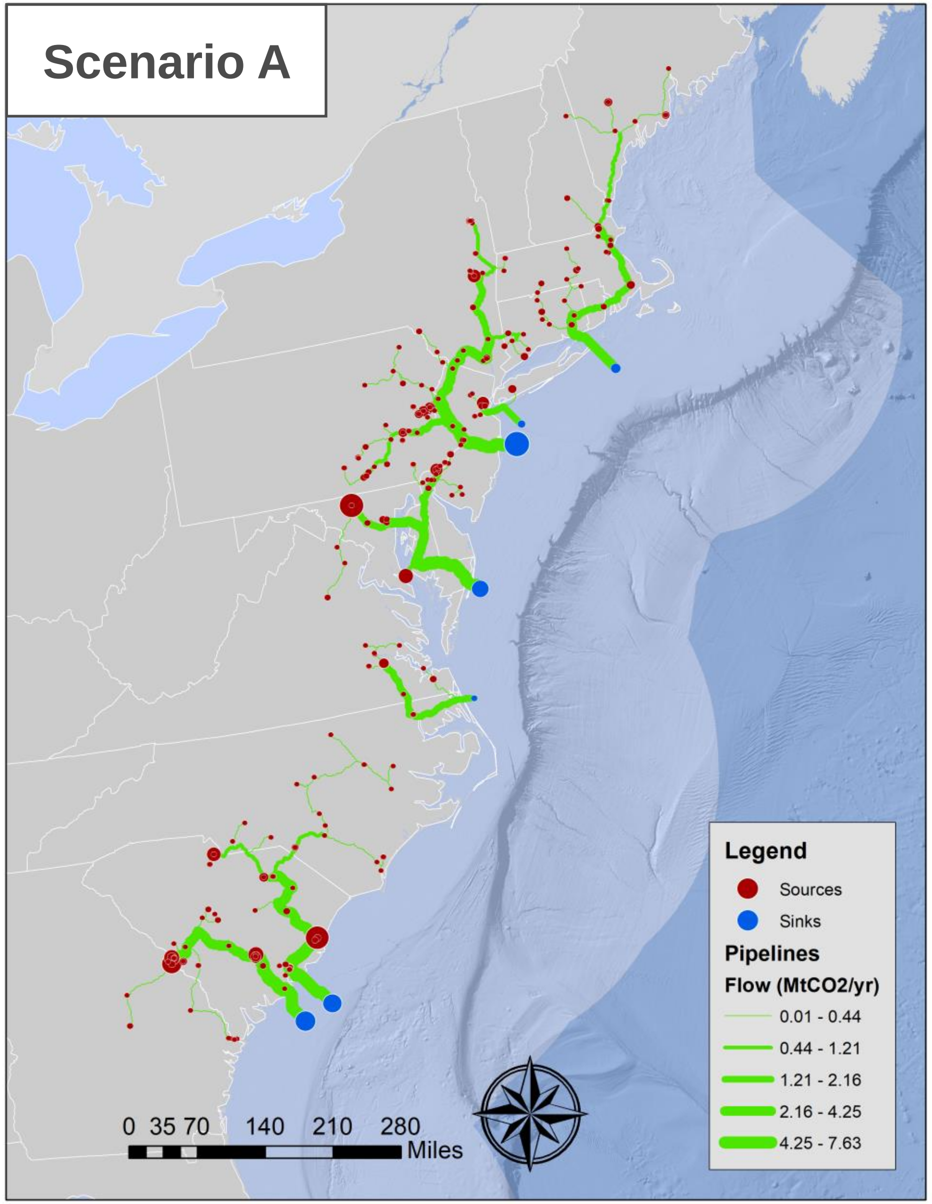
- **Sources:** 199
- **Streams:** 263.
- **Supply:** 31.5 $MtCO_2$/yr.

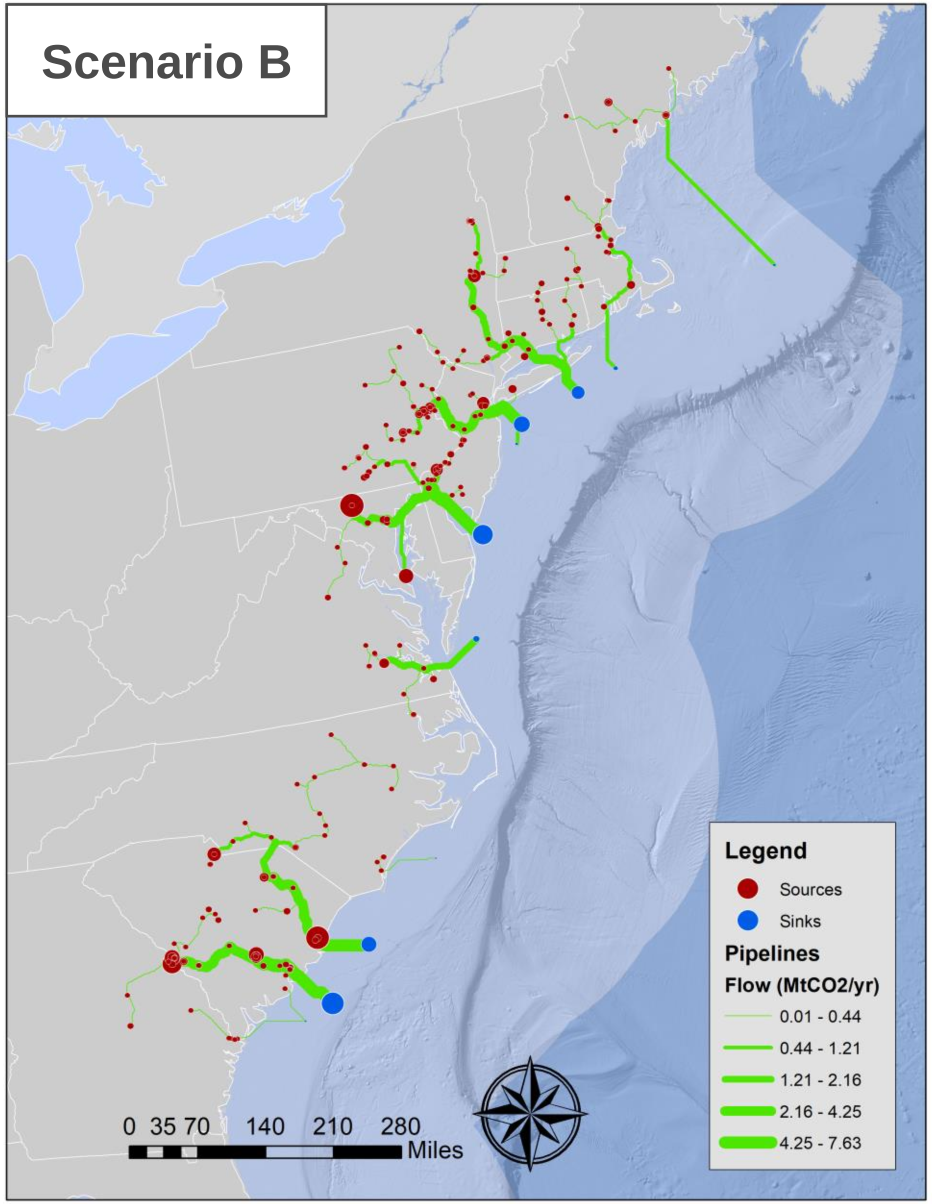
Storage

- Saline, offshore only.

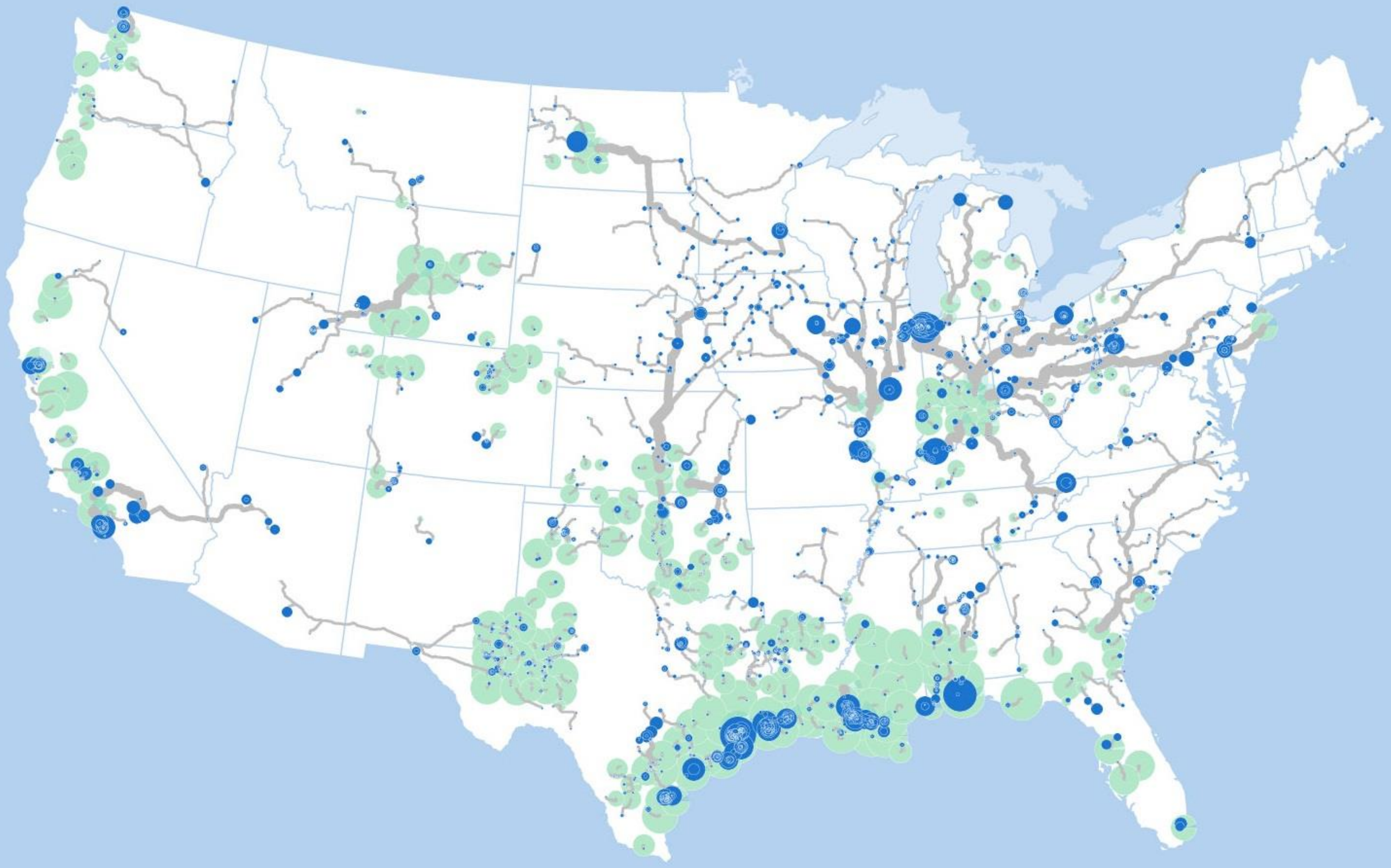
Scenario

- *SimCCS^CAP^* (capture all CO_2).
- **Scenario A:** Let model choose best pipeline route.
- **Scenario B:** Emphasize offshore transport.





Take Home Message



Why?

- Understand CCS at scale (net zero) using best possible data & models.
- Identify challenges & opportunities.

How?

- *SimCCS^{PRO}* software tools & databases.

What?

- **National infrastructure:** Massive CCS challenge to meet net zero targets.
- **Carbon deserts:** Areas without good storage but still must decarbonize.
- **Regional storage hubs:** Distributed storage is relatively abundant & requires less CO_2 transport.