CCS Modeling and Policy Design for the US Power Sector

Max(well) Brown

September 26th, 2025

Agenda

Talk split into two parts

1. (brief) Modeling of power system CCS (Brown et al., 2024)
2. Policy design for CCS power plants

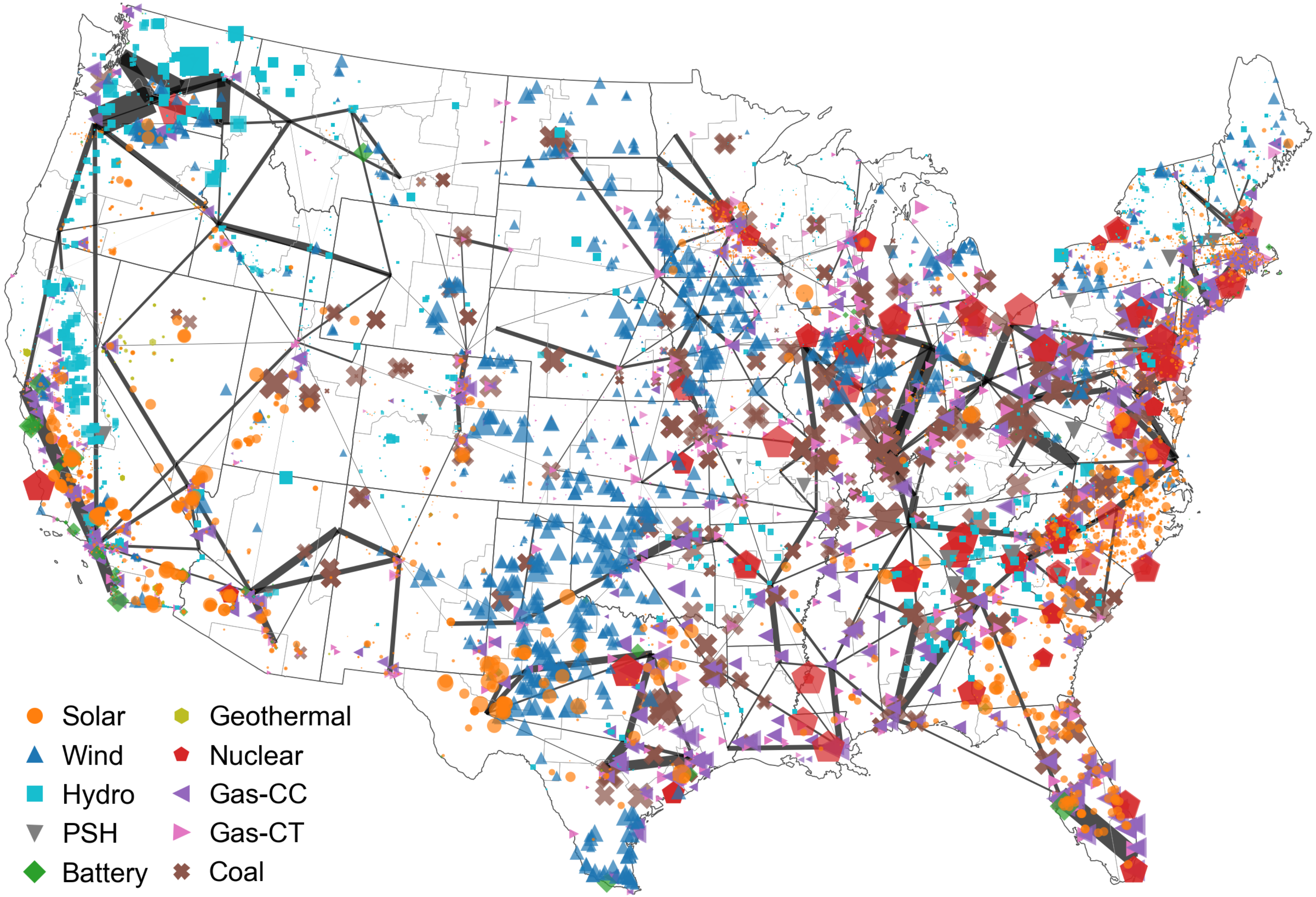
Regional Energy Deployment System

ReEDS

Linear program that solves for the cost-minimizing combination of investment in and operation of the US bulk power sector

Open-source:

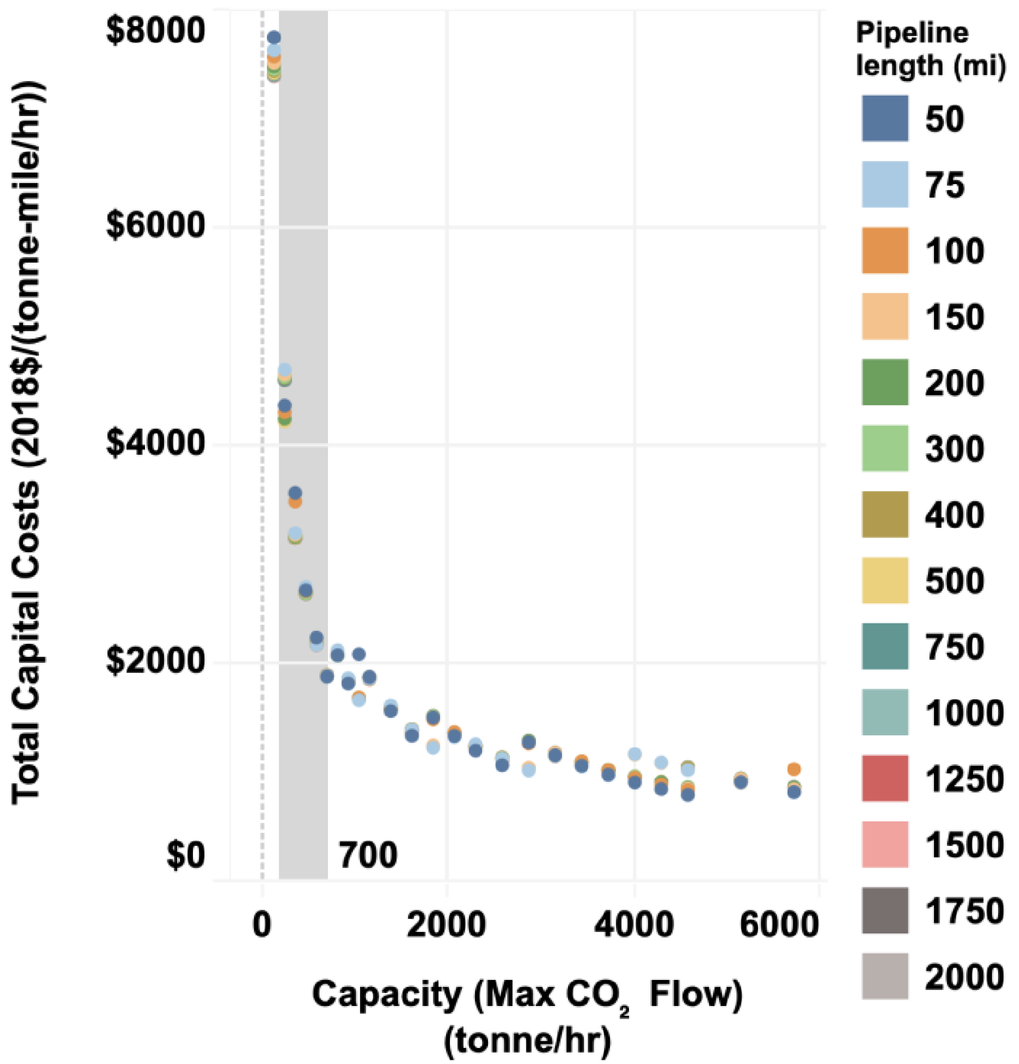
github.com/nrel/ReEDS-2.0



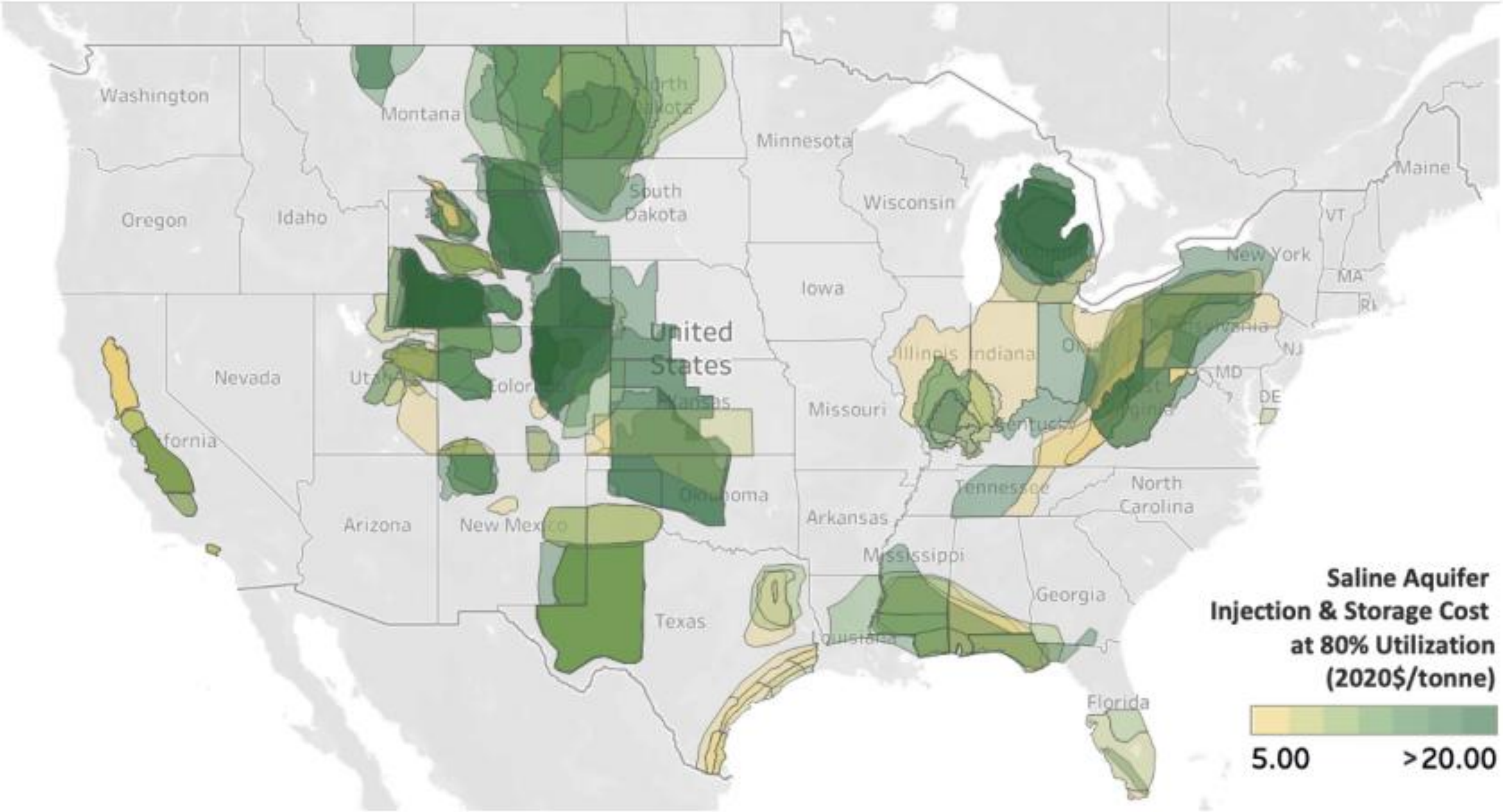
ReEDS enhancements

- Generating facility greenfield costs and performance (from NETL)
- Plant-specific upgrade costs and performance (from EIA)
- Reservoir-specific (NETL's CO2_S_M model):
  - Injection costs
  - Injection limits
  - Capacity limits
- Pipelines (NETL's CO2_T_M model):
  - Trunk lines for long-distance transport
  - Spur lines to connect nodes to reservoirs

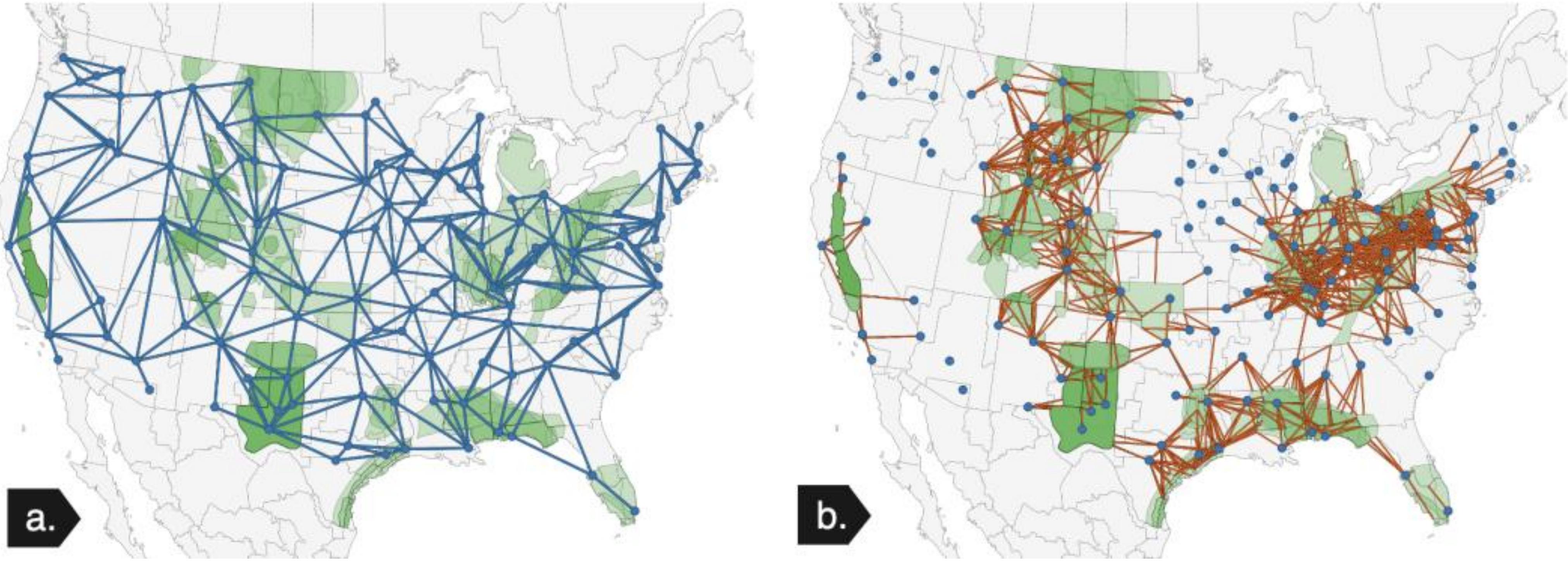
All publicly available (Brown et al. 2024)



Reservoir break-even injection and storage costs



Pipeline network



a. Trunk lines
b. Spur lines

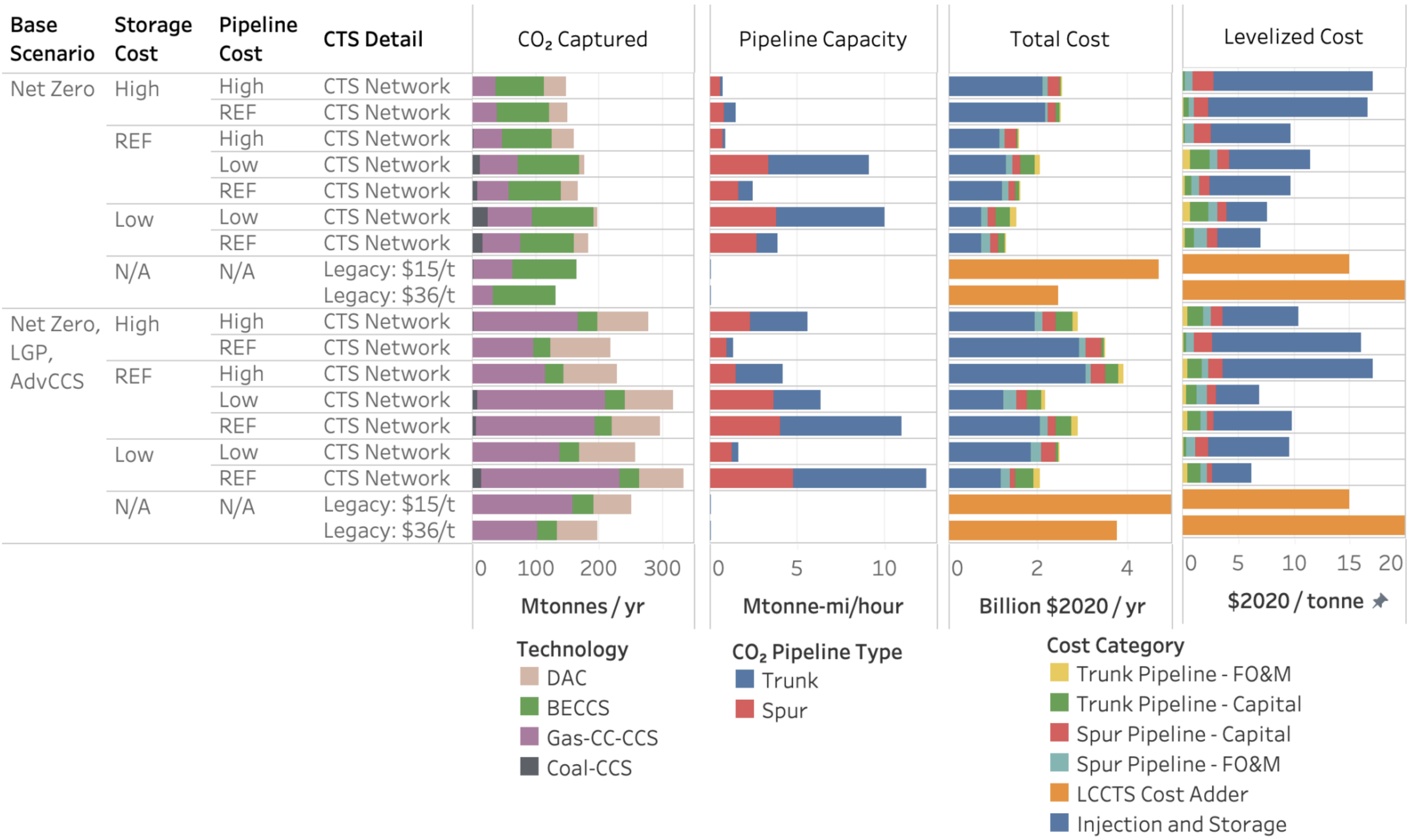
Scenario exploration (first paper)

- Reference case (includes IRA incentives and 45Q)
- Net Zero (0 net emissions by 2050)
- Net Zero, Favorable (… + low CCS costs, low gas price, high RE cost)

… w/new features ('CTS Network') and simple cost ('Adder')

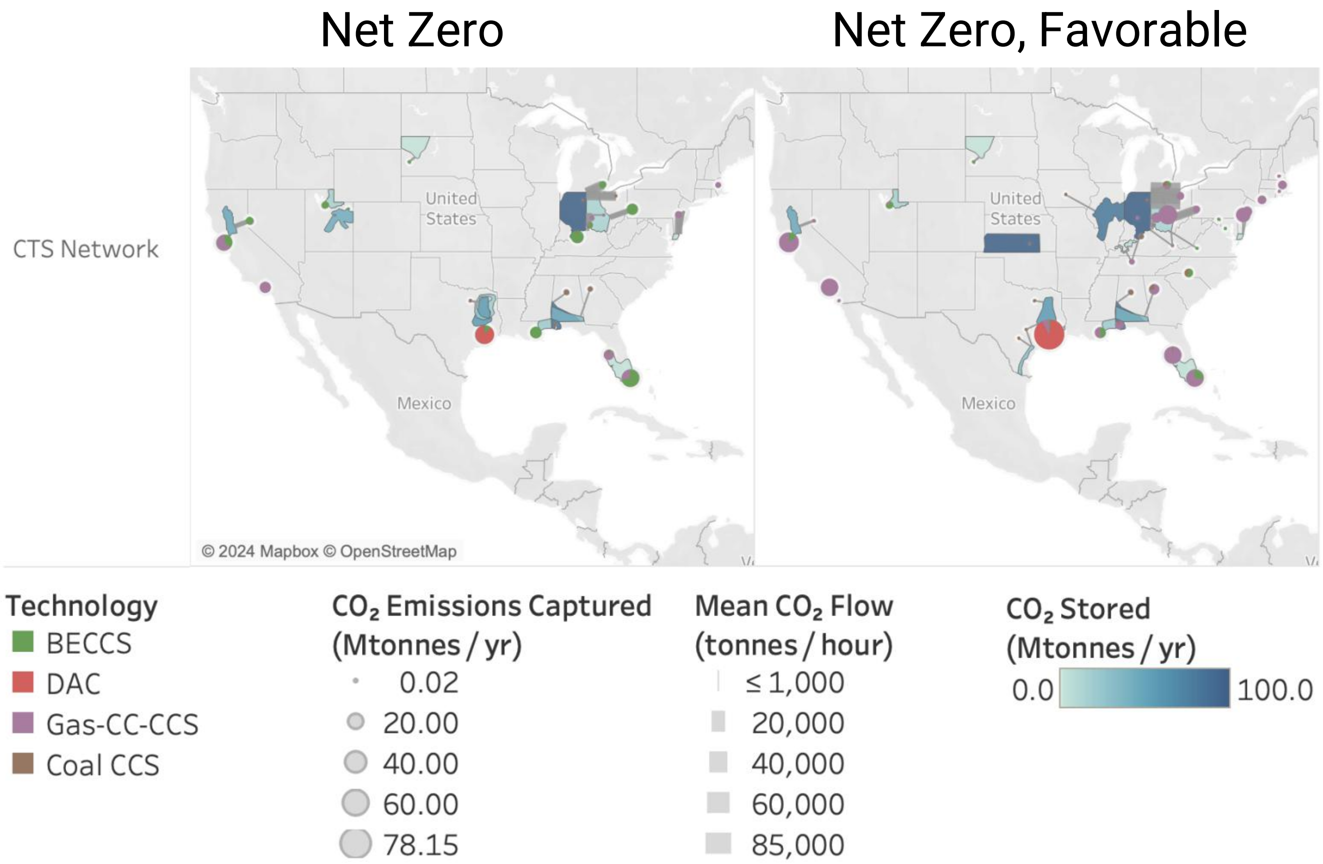
Tonnes captured, pipeline capacity, and costs

- Pipeline capacity very sensitive to cost assumptions
- Levelized cost dominated by injection and storage



Network buildout, 2050

- National network buildout limited, localized
- Reservoirs co-located with generators
- DAC cited in SE Texas (low-cost)



Policy design

A short story…

Research question

What is the economic efficiency of incentives based on CO_2 captured [versus] generation for coal-fired electricity generators?

Logic [I]

Without CCS:

Price O&M Fuel Costs Generation

$$\max_{Q_i} \quad \pi_i = \left(p - c_i^v - c^f H_i\right) Q_i$$

With CCS:

Net CCS Subsidy Upgrade Costs

$$\max_{Q_i, R_i} \quad \pi_i^c = \left(p - c_i^v - c^f H_i - H_i \eta_i \beta_i \theta]\right) Q_i - c_i^u R_i$$

H_i: heat rate (mmBTU/MWh)

Note: simplified here, omitting extra terms in paper

Logic [II]

Plant will upgrade when:

$$\pi_i^c - \pi_j > 0 \;\Rightarrow$$

$$p\,\Delta Q + \eta_i \beta_i \theta\, Q_i > \Delta c^v\, Q + c^f\, \Delta H \Delta\, Q + c_i^u R_i$$

ΔRevenue

Net Subsidy for CO2 Stored

ΔO&M

ΔFuel Costs

Upgrade Costs

Note relationship with respect to fuel combustion:

$$\frac{\partial(\pi_i^c - \pi_j)}{\partial(H_i Q_i)} = \eta_i \beta_i \theta - c^f$$

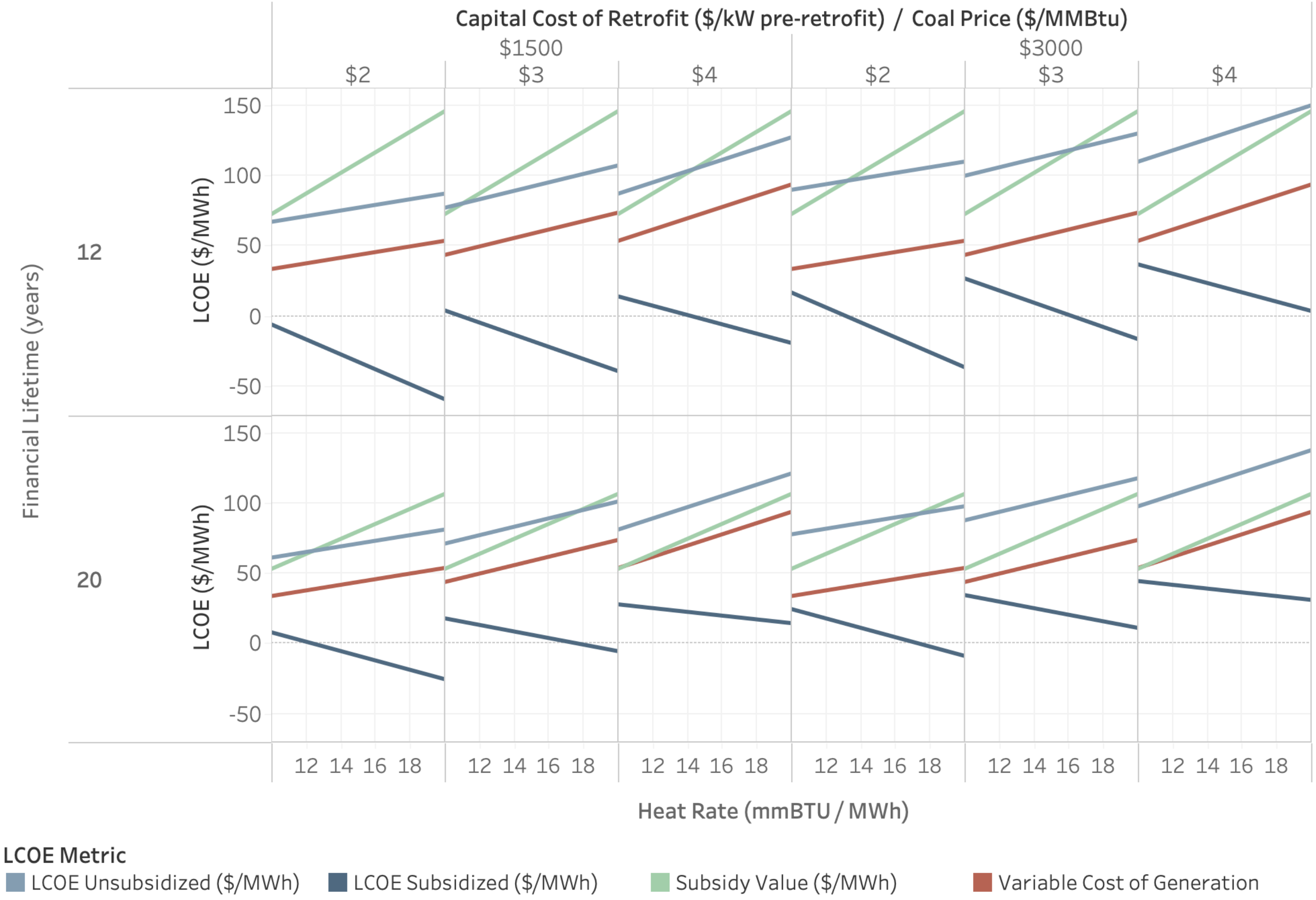
Analytical model – coal retrofits

Q: When increasing the heat rate, what increases more:

(a) fuel costs
(b) CO2-stored incentive

?

A: Incentive



Scenario design

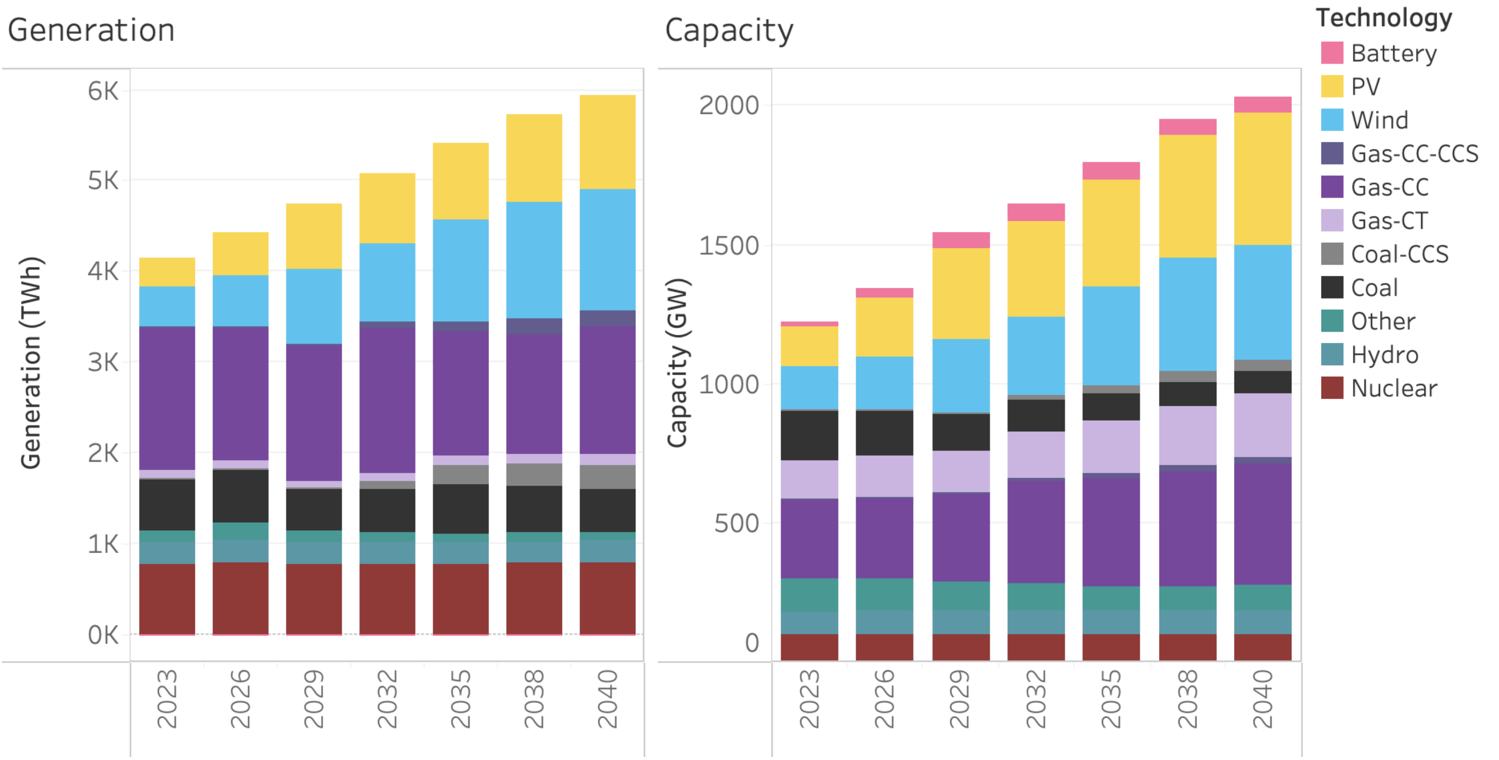
- Policies…
  - Subsidy based on CO_2 stored based on 45Q (“CO2”)
  - Generation-based subsidy to match that generation level (”GEN”)
  - Only looking at Coal-CCS for now

- Renewable energy costs – Low/Reference/High

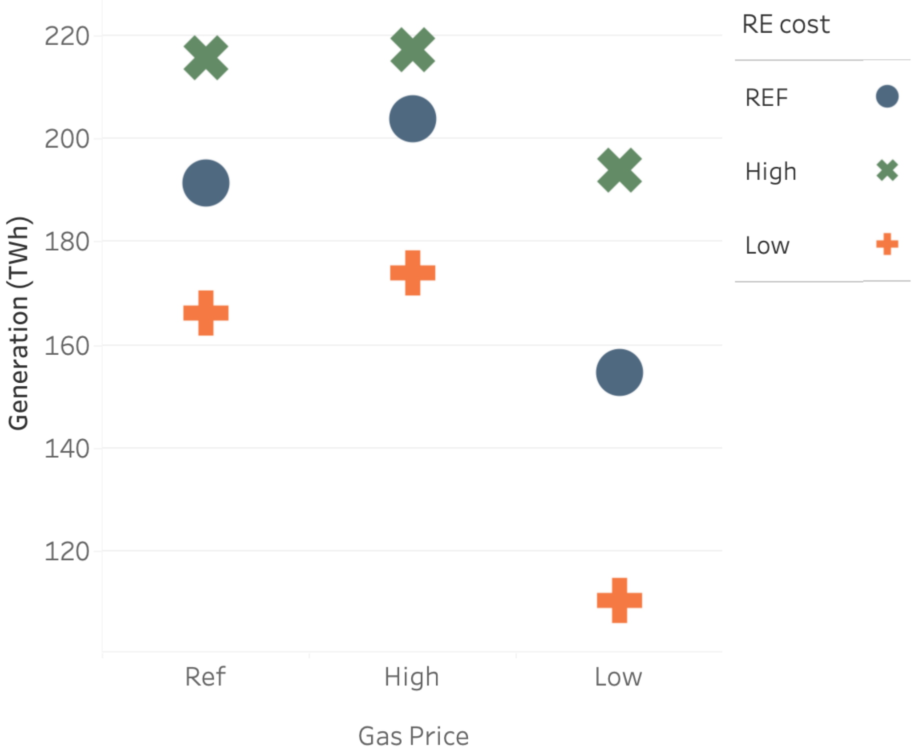
- Natural gas prices – Low/Reference/High

Electricity generation and capacity

Generation and Capacity – Reference Case

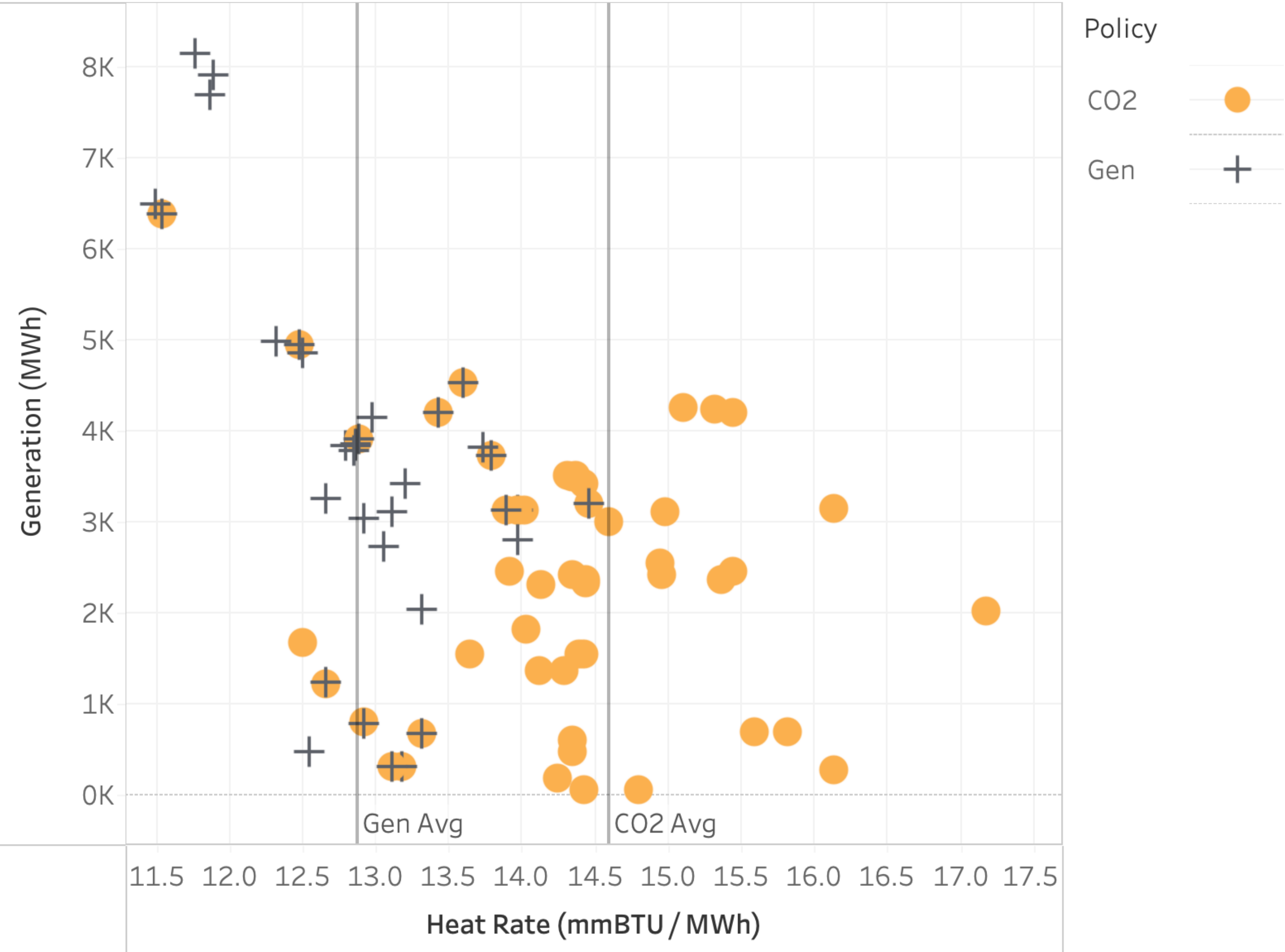


Coal-CCS Generation, 2035



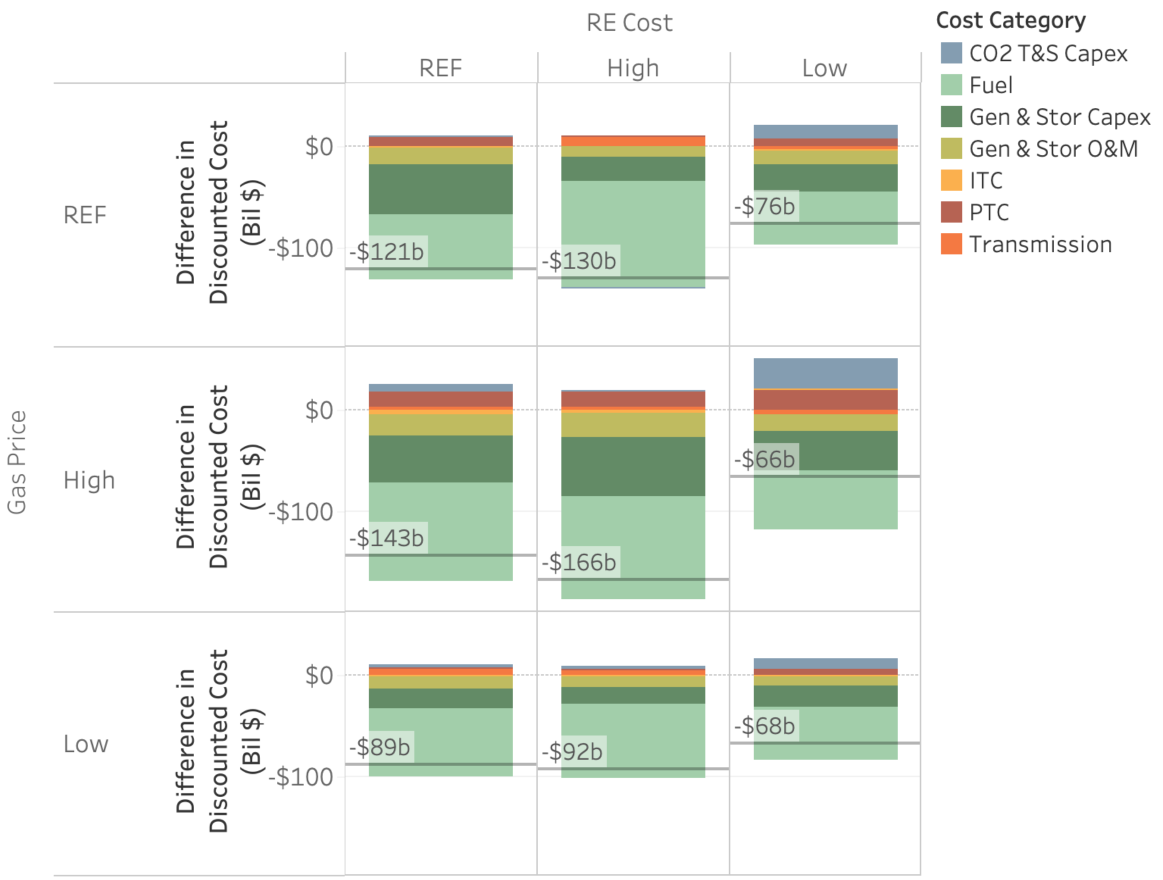
Generation by fuel combustion rate

- Theory holds
- CO2 based incentives result in higher heat rate units generating more electricity



System and Policy Costs

Change in Discounted System Cost



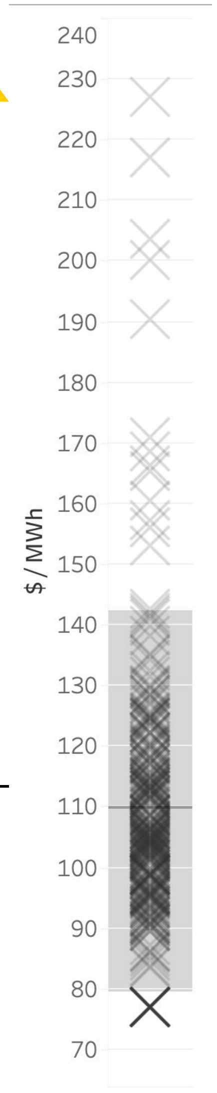
Generation Subsidy ($/MWh) - 2035

		RE Cost		
		Ref	High	Low
Gas Price	Ref	$ 81.39	$ 90.97	$ 84.33
	High	$ 93.48	$ 91.01	$ 87.32
	Low	$ 78.90	$ 84.90	$ 81.12

Discounted Change in Gov Expenditures ($billion)

		RE Cost		
		Ref	High	Low
Gas Price	Ref	$ -9.83	$ -10.46	$ -7.18
	High	$ -11.08	$ -11.15	$ -9.96
	Low	$ - 8.52	$ - 8.94	$ -5.66

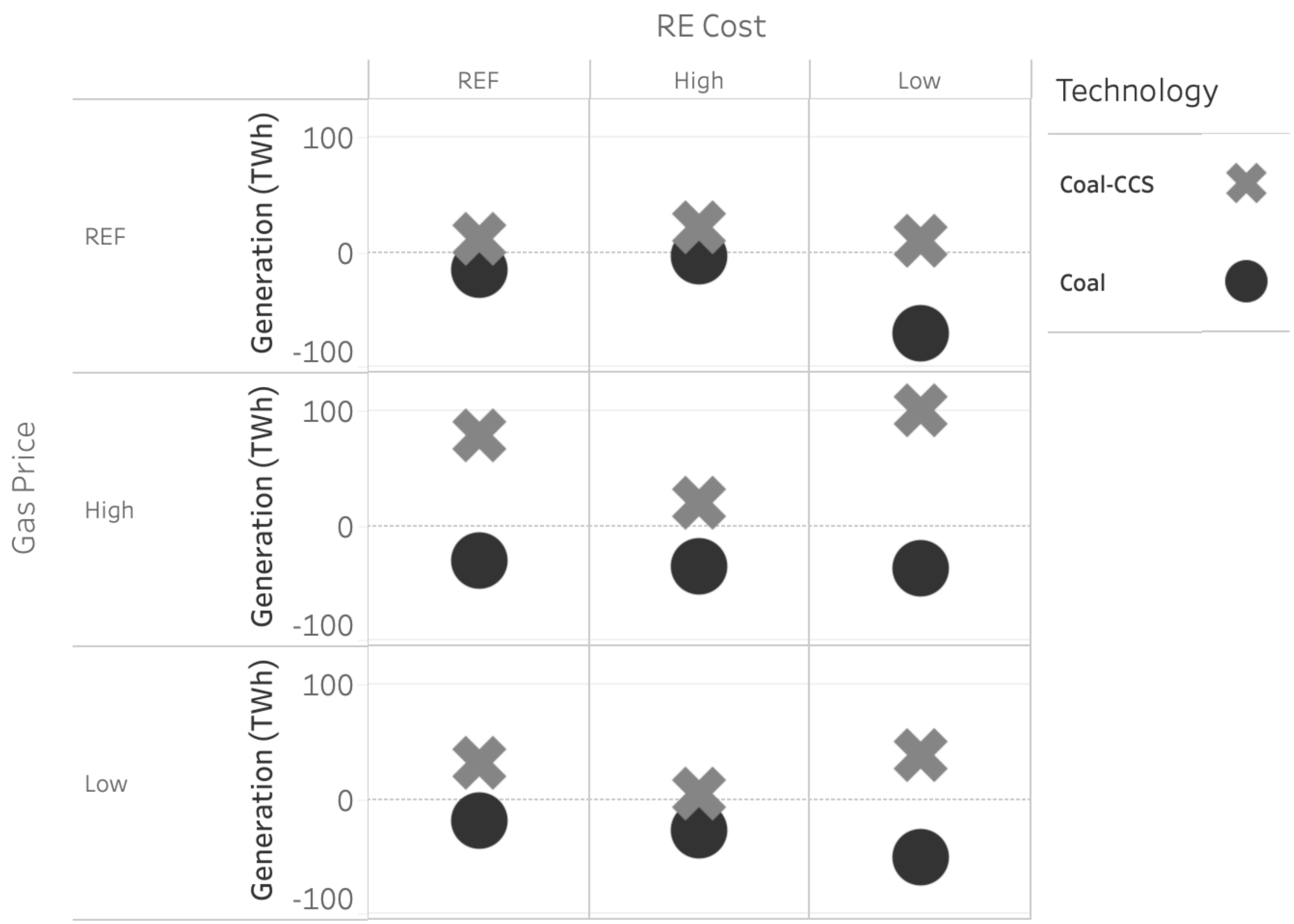
CO2-based per MWh subsidy



Longevity

- When inefficient units are upgraded, they do not survive as long
- Retiring less-efficient units with ‘Gen’ incentive policy leads to reduced unabated coal generation and greater Coal-CCS longevity

Difference in 2050 generation level (Gen [minus] CO2)



Emissions

- More fuel consumption means more emissions, even at high capture rates
- Higher-cost units (with higher heat rates) face greater retirements in 2040 under 'Gen' scenario
- Simple average difference of ~60 million tonnes CO_2 per year (CO_2 [minus] Gen)

Cumulative CO_2 Emissions: 2023-2050

		RE Cost		
Policy	**Gas Price**	Ref	High	Low
CO2	Ref	24,447	25,657	20,373
	High	24,543	25,148	21,437
	Low	23,587	24,487	20,900
Gen	Ref	22,998	24,042	19,660
	High	22,815	23,465	19,660
	Low	22,095	23,090	19,193

Difference (CO2 [minus] Gen)

Gas Price	Ref	High	Low
Ref	1,448	1,615	1,713
High	1,728	1,683	1,777
Low	1,492	1,397	1,707

Policy takeaways

- Units with higher heat rates incentivized more with CO2-stored based incentives

- Equivalent, generation-based incentives result in:
  - Upgrades of more fuel-efficient plants
  - Lower system costs
  - Reduced government expenditures
  - Survival of more efficient coal units by 2040
  - Reduced emissions

  … not much change in CCS system buildout

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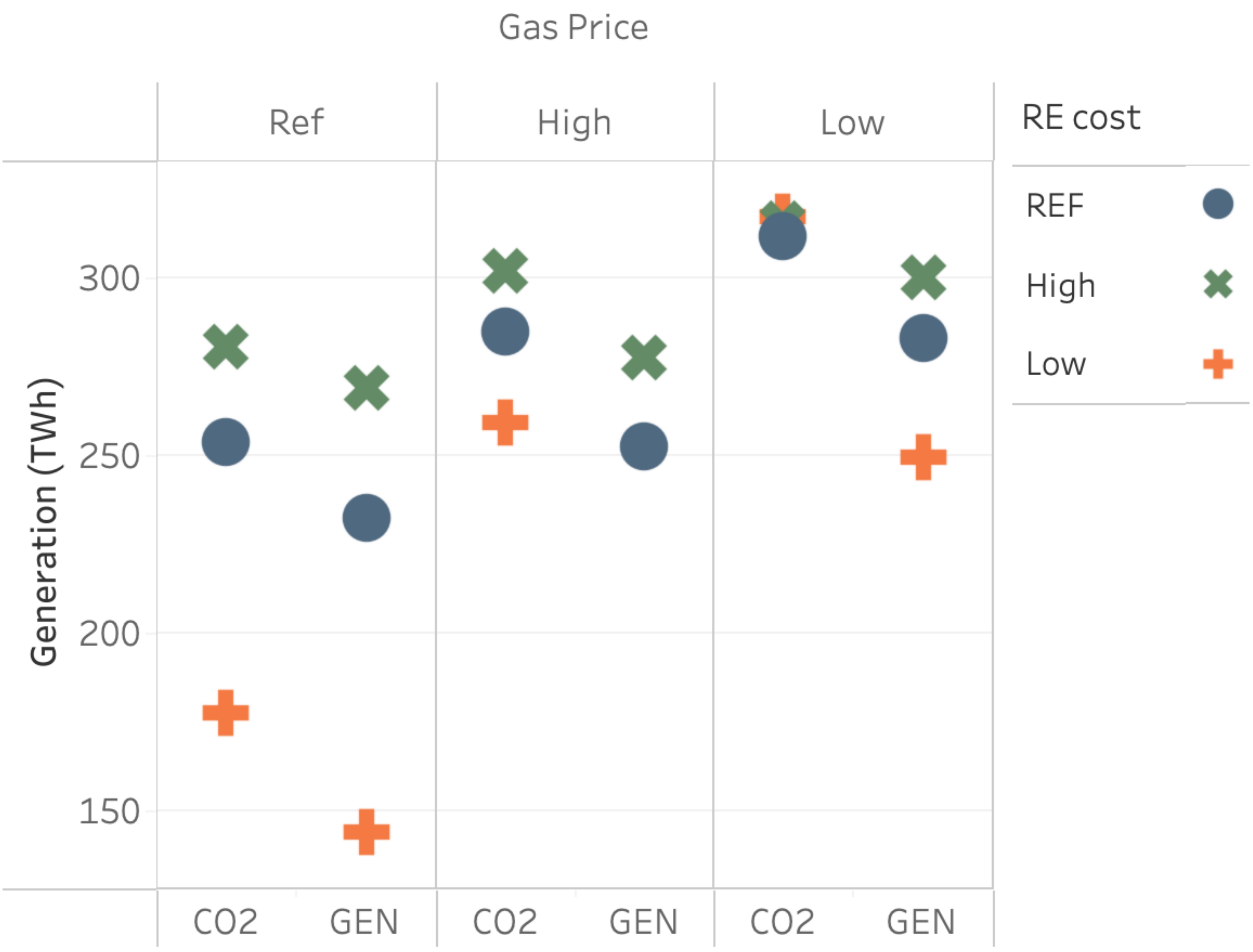
maxbrown@mines.edu

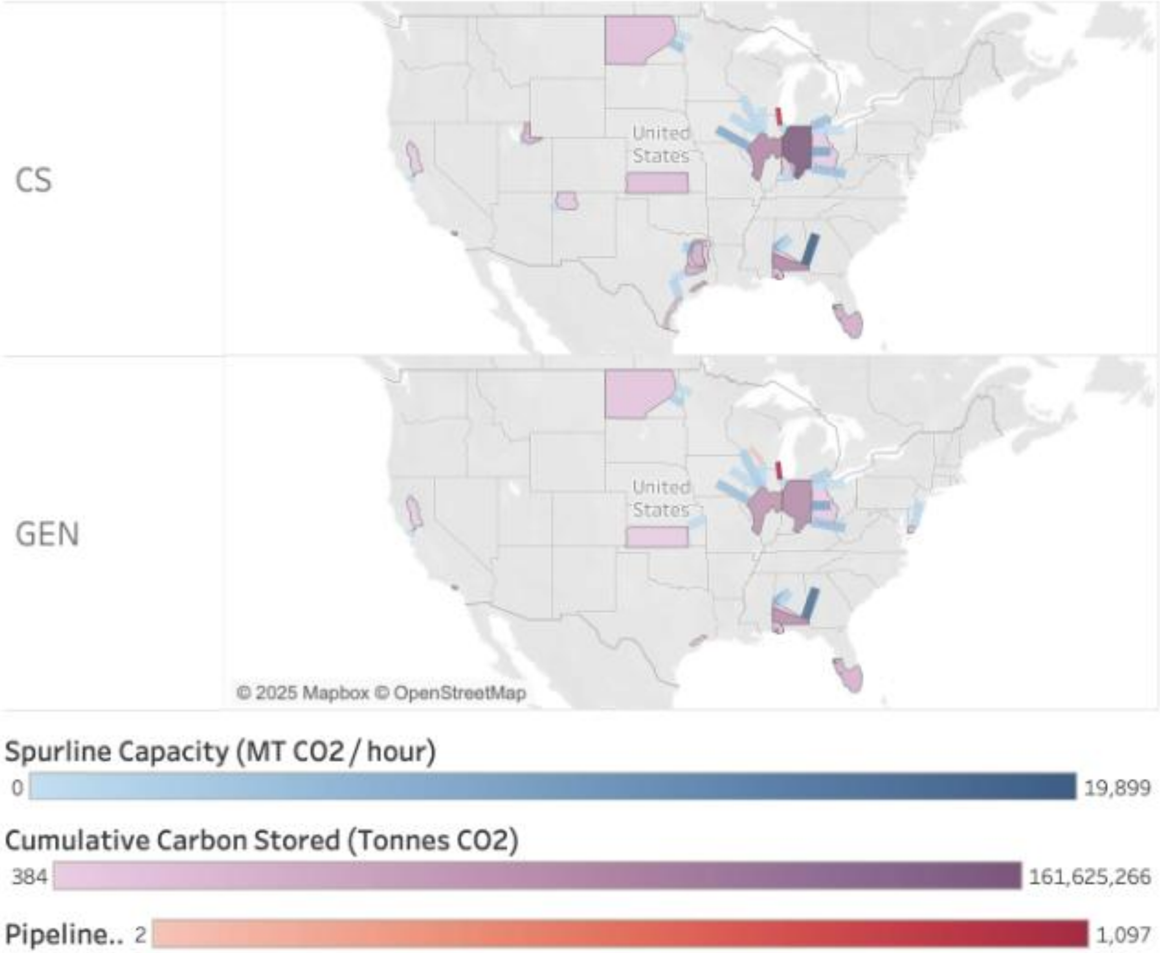
Logic

π_i	\$	Profit
p	\$/MWh	Price for electricity
c_i^v	\$/MWh	Variable and operating costs (excl. CCS)
c_i^o	\$/MWh	CCS operating and maintenance costs
c^f	\$/mmBTU	Fuel cost
H_i	mmBTU/MWh	Plant heat rate
Q_i	MWh	Generation
η	\$/tonne CO2	Storage-based subsidy
β_i	%	CO2 capture rate
θ	tonnes CO2/mmBTU	Fuel emission intensity
c_i^u	\$/MW	Capital cost of CCS installation
R_i	MW	CCS retrofit capacity installed
γ_i	\$/MWh	Generation-based subsidy

Unabated coal generation - 2040



CO2 Network Buildout - 2040



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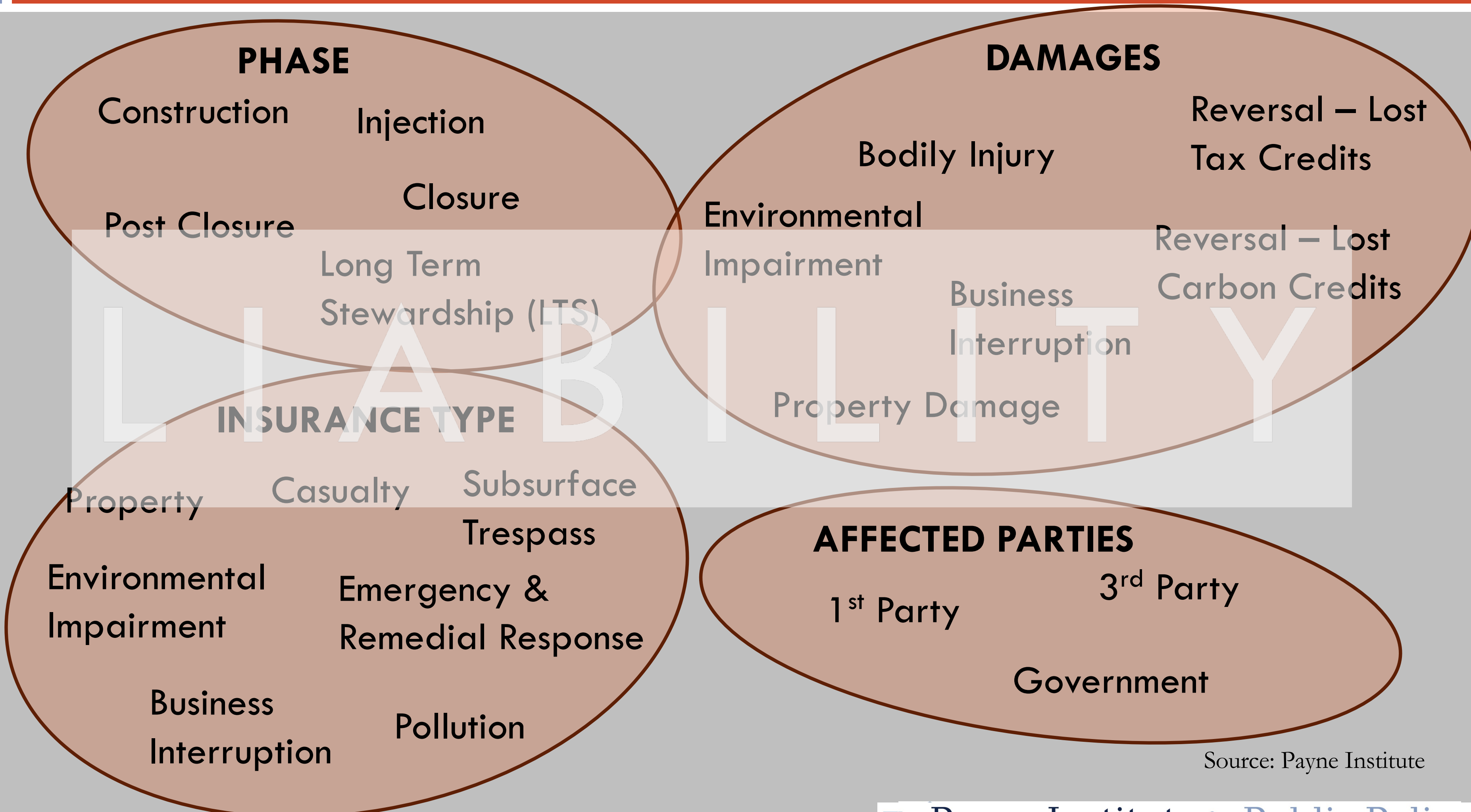
Addressing Geological Sequestration Liability in the U.S.

Brad Handler
Program Manager, Sustainable Finance Lab
April 10, 2024

The CCS Liability Morass



Source: Payne Institute

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Risk Mitigation By Project Phase

Commercial Insurance?	Construction	Injection	Closure	PISC
✓	**Worker Injury** Self Insurance, Commercial Insurance	→	→	→
✓		**Operations - General Liability** Self Insurance, Commercial Insurance	→	→
		Induced Seismic - Property Damage Self Insurance	→	→
✓		**Leakage - Loss of Tax or Carbon Credits** Self Insurance, Commercial Insurance[1], Trust Fund[2], Buffer Pool of credits	→	→
		Leakage – 3rd Party Property Damage, Bodily Injury Self Insurance, Commercial Insurance[3], Trust Fund	→	→
			Insufficient Funding Financial Assurance[4]	

[1] Brokers are promoting; AON has placed one policy to date; not clear of breadth of capital support from insurers

[2] Trust can be funded from project or independently; a "tipping fee" (e.g. a $/ton taken from any credits earned) is one option

[3] Thus far, "placeholder" policies signed – more like Intent to Purchase – to satisfy this portion of Financial Assurance in EPA Class VI permit applications

[4] Mandated by EPA. Can be established through Financial Statement test, Corporate Guarantee, Trust Fund, Letter of Credit, Surety Bonds, and Insurance. Note that Financial Assurance requirements include covering environmental impairment (Note 3)

Source: Payne Institute

Long Term Stewardship Framework

Various parties have considered how, after a defined PISC period, developer might be released from liabilities. Generally, 3 elements:

1. Creation of entity (public or semi-private)
   - Manage LTS monitoring, bear responsibility for payouts
   - Possible involvement of this entity before LTS phase.
     - Logic: if entity is responsible for payouts, more care in project permitting decisions
   - Handoff from developer could be time-based or performance-based
2. Creation of a Fund/Trust
   - For monitoring, compensatory damages
   - Pooling of funds raised from individual projects' Tipping Fees
     - Regularly evaluate size given risk pooling and time post-injection period
3. Legislative action to determine the extent of release of liability

Versions of LTS Frameworks in U.S.

U.S. State	Years to Transfer[1]	Storage Fund Fee ($/Metric Ton)	Extent of liability release
ND	10	$0.07	Unlimited
KS		$0.05	None
TX[2]	0	$0.10	Unlimited
IN	10	$0.08	Unlimited
WY	20	Not specified	Capped at storage Fund balance[3]
MT	30	Not specified[4]	Unlimited
LA	10	Not specified	Capped at Storage Fund balance[5]
IL			Applies only to FutureGen projects

[1] Following certification of closure; [2] Onshore only; [3] Unclear what happens if liabilities exceed this; [4] Also must provide Financial Assurance for 30 years of monitoring; [5] Operator responsible if liability above this amount

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Building Security for LTS Handoff

Site Selection

Estimated thousands of years of sequestration

Geochemistry suggests risks decrease over time after injection is finished

Strong Regulation of Well, Injection, Closure

Protecting against leaks

Financial Assurance

Ensuring adequate funding for closure, PISC, and to handle emergency releases

Funding L-T Care

Sourced from "Tipping Fees" or a portion of carbon credits

Funds ongoing monitoring and response to any leakage

Handoff

All of the previous steps mitigates risk for public entity to assume responsibility

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