The Spatial Deployment of Carbon Capture and Storage with a Price on Carbon Dioxide

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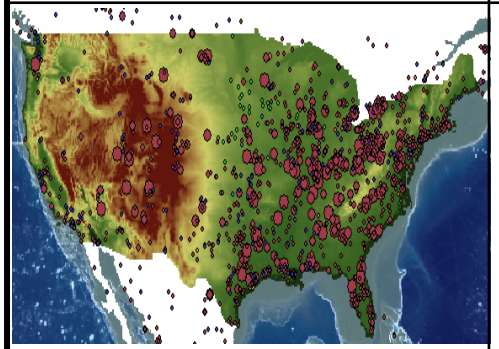
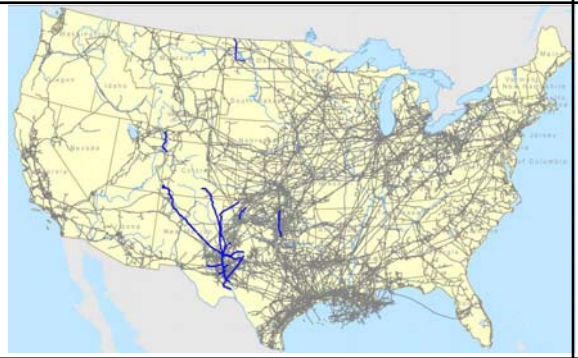
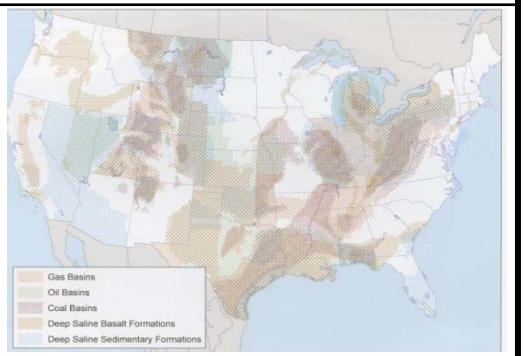
Carbon Capture and Storage

Point Sources[1]	Pipeline Infrastructure[2]	Injection Reservoirs[3]
		
Known	Unknown	Unknown

[1] NETL (2007), [2] PHMSA (2003), [3] Dooley et al. (2006)

Carbon Capture and Storage

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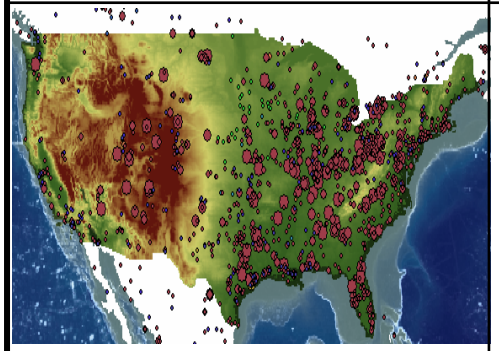
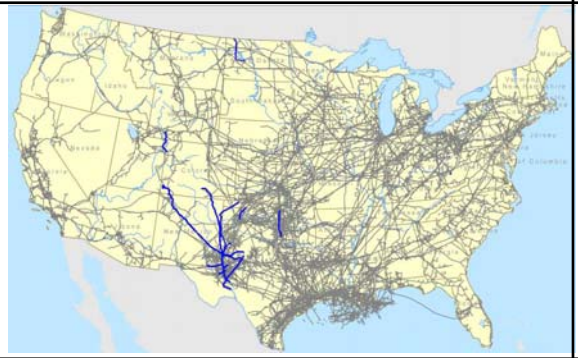
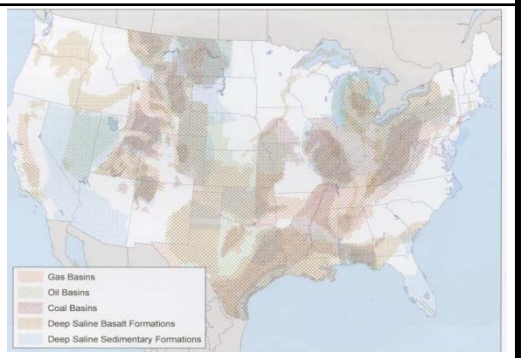
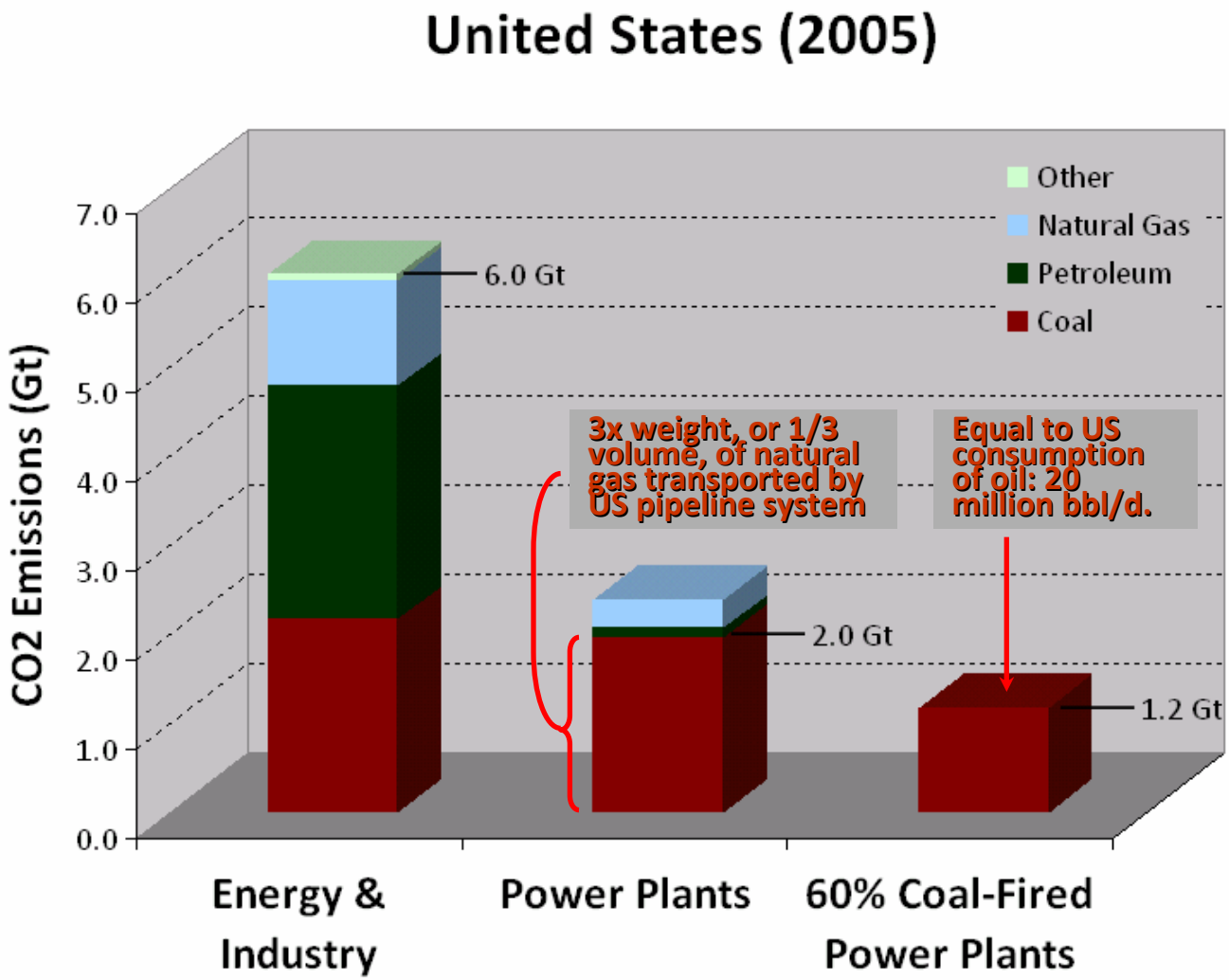
		
Known	Unknown	Unknown

- CCS is an integrated system of *costly* technologies coupled together over space.
- CCS needs an economic incentive in order to be deployed.

[1] NETL (2007), [2] PHMSA (2003), [3] Dooley et al. (2006)

Magnitude of CO_2 Production[1]



[1] From Pacala and Socolow (2006), MIT(2007), and EIA: http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

Preview

- An economic incentive will be necessary for CCS to be deployed.
- Introduce a model that spatially deploys integrated CCS systems based on CO_2 price.
- *Marginal* deployment varies with price level.
- Suggest "better" CO_2 prices.

Market-Based Mechanisms

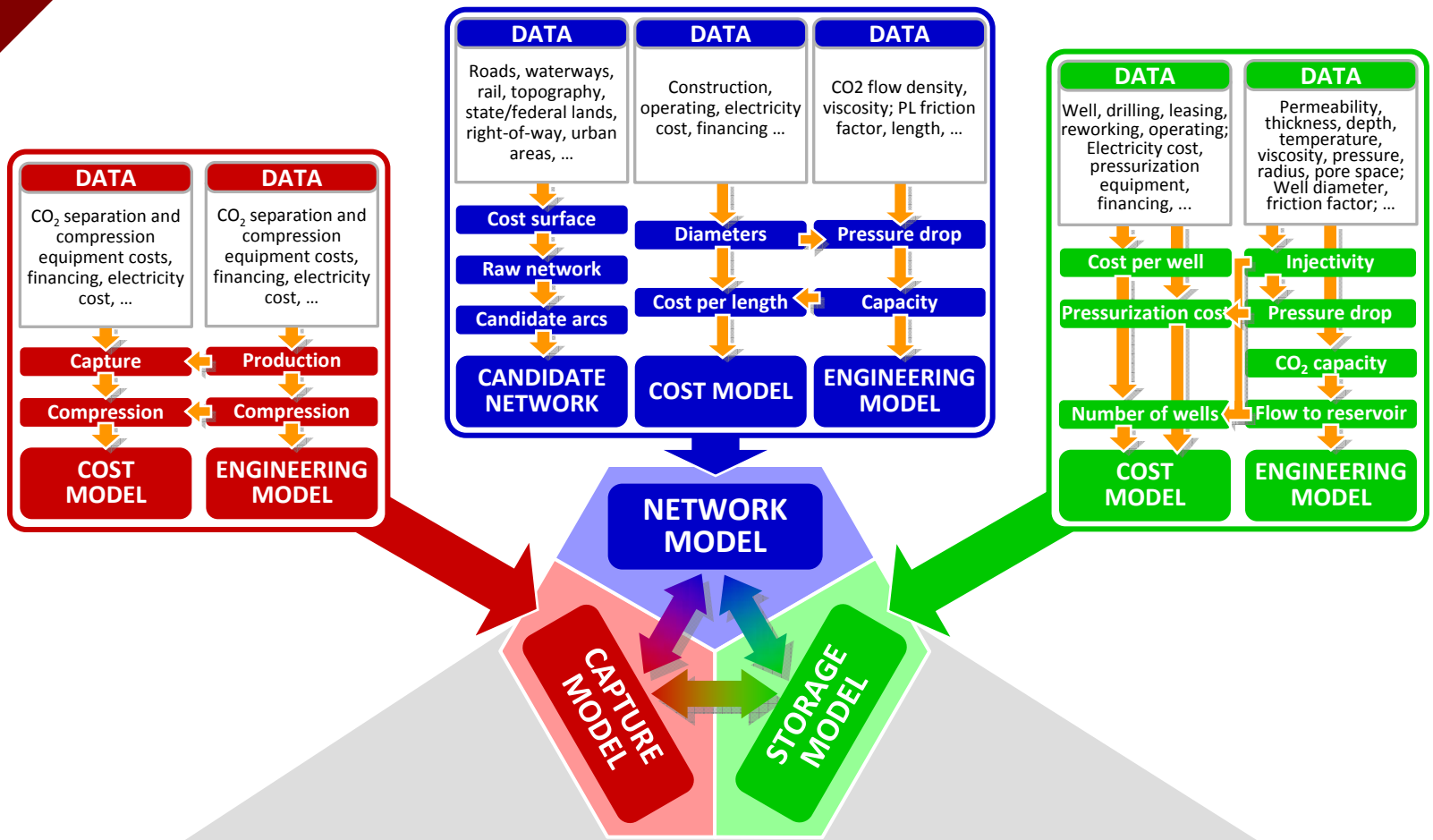
1. **Cap-and-Trade Permit System**
   - Set quantity, market determines price.
   - Price volatility
2. **Tax on CO_2 Emissions**
   - Set price, market determines quantity.
   - Quantity volatility

Theoretically equivalent in a certain world

3. **Optimal: Hybrid, cap-and-trade with price "safety valve."**
   - Limit maximum price to reduce volatility
   - *More like a CO_2 tax in context of climate change.*

	Permits	Taxes
Economic optimality:	Optimal if certain about quantity	Optimal if certain about cost per tonne
Political economy:	More risks for distributional effects	More risks for efficiency effects
	Probably more politically tenable	Probably simpler to implement

Scalable Infrastructure Model for CCS: *SimCCS*[1]



COSTS	SPATIAL DEPLOYMENT	CO_2 FLOWS	GENERAL
Cost to deploy CCS infrastructure	**Where to capture and/or release CO_2**	**CO_2 amount to be captured at each source**	Amount of CO_2 cost-effectively sequestered
Capture, transport, and storage costs	Location of capture-ready CO_2 sources	**How much CO_2 should be stored in each reservoir**	Scale of CCS infrastructure
Carbon tax ($/tonne)	**Which reservoirs should inject/store CO_2**	**CO_2 pipeline capacities**	Policy implications
Cap and trade pricing	**Dedicated CO_2 pipeline *network***	**CO_2 allocation between sources and reservoirs**	Tradeoff between capture, transport, and storage

[1]Middleton and Bielicki (2009a, 2009b), Bielicki (2008c)

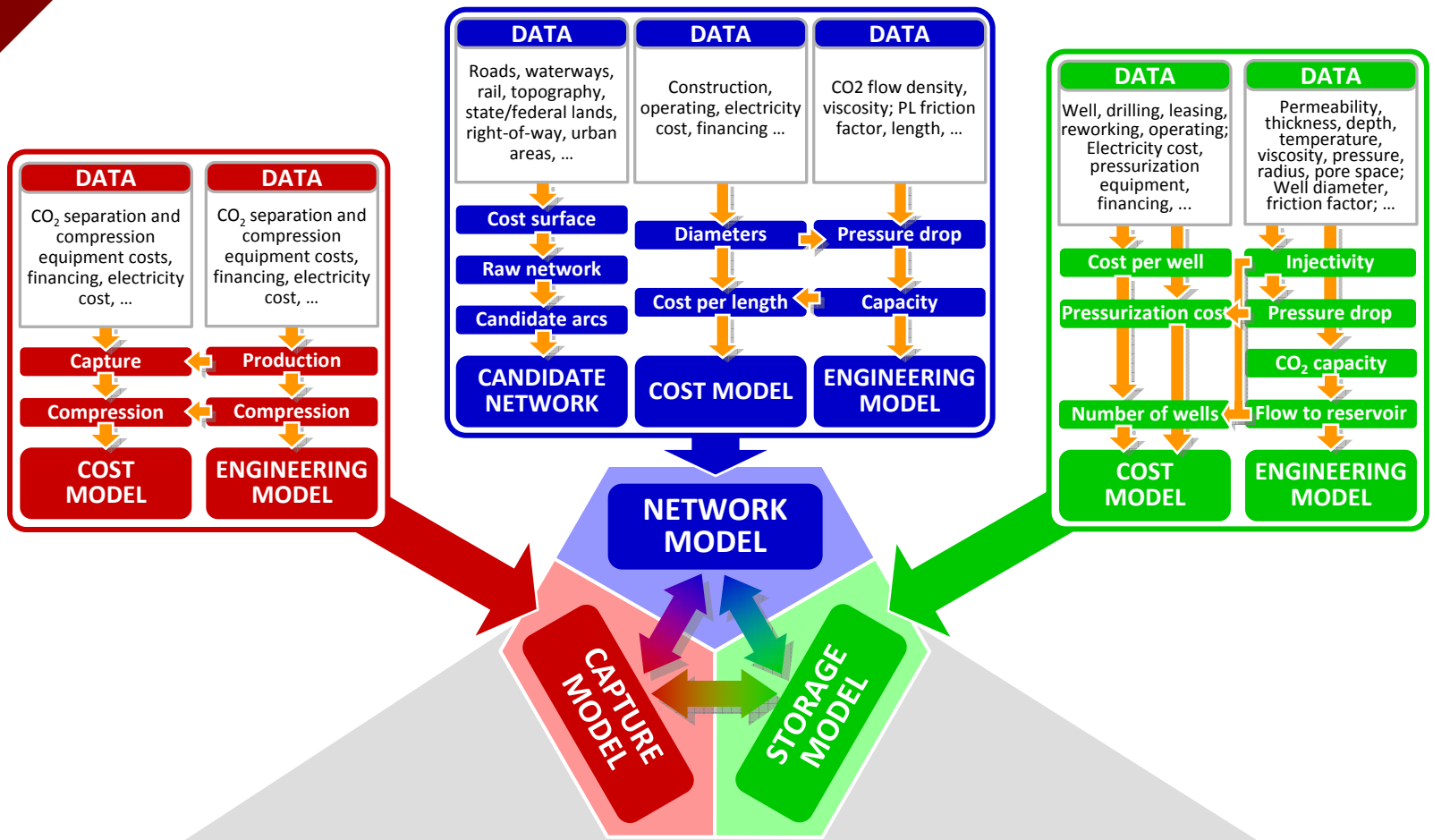
CCS Problem Components

Simultaneously and optimally decide:

1. which CO_2 sources to use
2. how much CO_2 to capture at selected sources
3. which geological reservoirs to open
4. how much CO_2 to inject into each reservoir
5. where to construct pipeline *network*
6. what diameter pipeline to build
7. how distribute CO_2 amongst supplies/demands

SPATIAL DEPLOYMENT	CO_2 FLOWS
Where to capture and/or release CO_2	CO_2 amount to be captured at each source
Location of capture-ready CO_2 sources	How much CO_2 should be stored in each reservoir
Which reservoirs should inject/store CO_2	CO_2 pipeline capacities
Dedicated CO_2 pipeline *network*	CO_2 allocation between sources and reservoirs

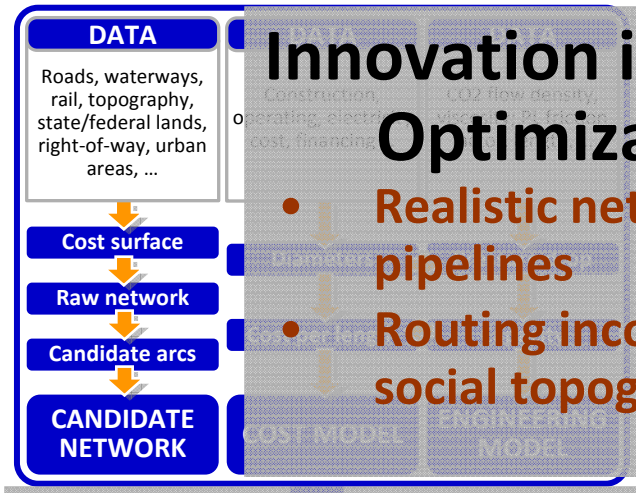
SimCCS: Engineering Economic Models



Integrated coupling of technologies and geologies:

- Estimate costs and capacities individually
- Fixed and variable costs for each component interact
- Potential for returns to scale to reinforce each other

SimCCS: Engineering Economic Models



Innovation in Geospatial Optimization:

- **Realistic network with trunk pipelines**
- **Routing incorporates physical and social topography**

Sources:

- Adjusted from literature review (IPCC, 2005)
- Compression/ pressurization equipment (IEAGHG 2002)

Pipelines:[1]

- Construction, pressurization, etc.
- Min/Max pipeline capacities
- Incorporates returns to scale with increasing diameter

Reservoirs:[1]

- Geologic parameters and conditions

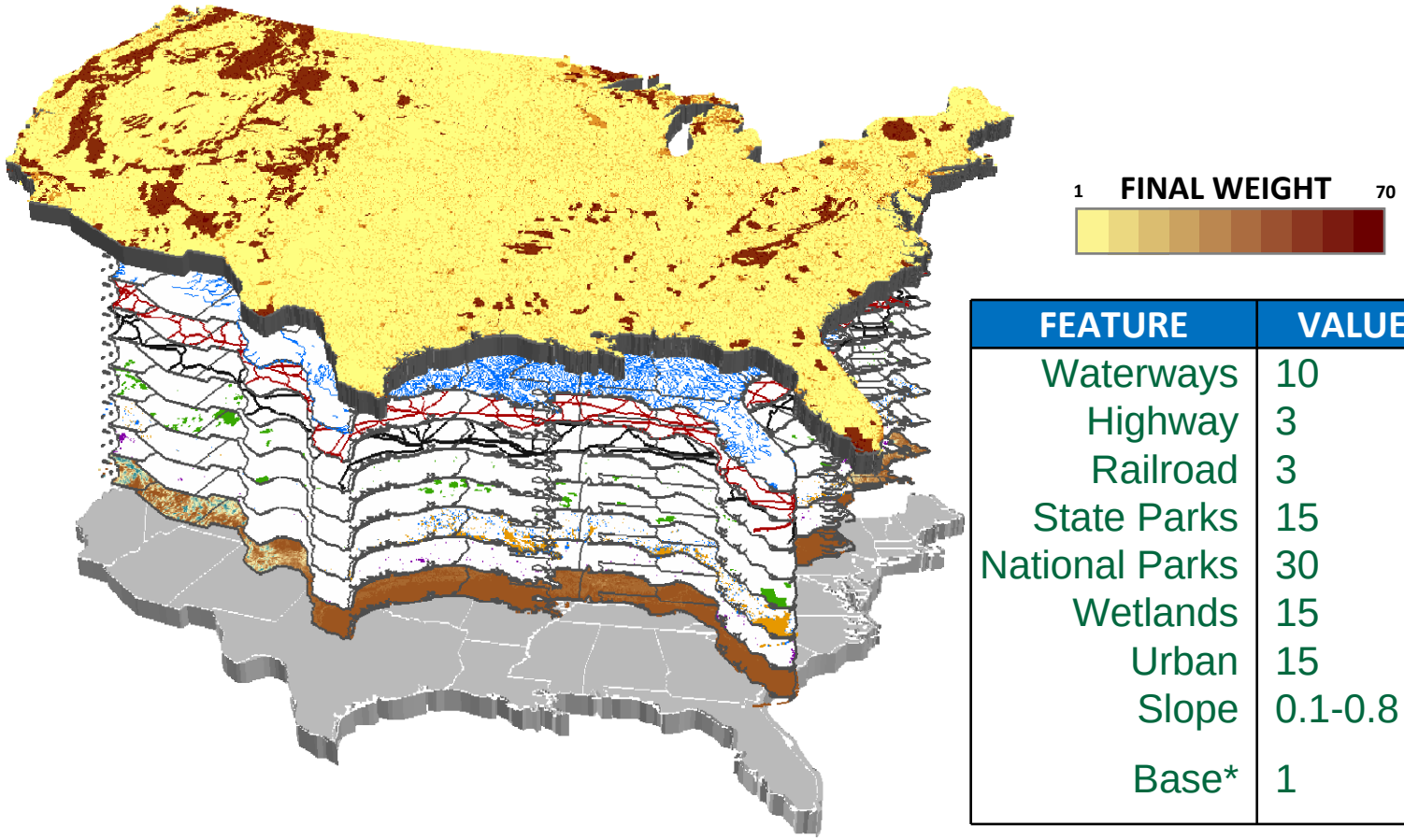
Includes relevant CO_2 properties

Basic thermodynamics, fluid mechanics, etc.

[1]Bielicki (2008)

Routing Pipelines

- **Shortest path algorithm incorporates social and physical topography:**
  - Relative cost of routing through cell (1km x 1km)



FEATURE	VALUE
Waterways	10
Highway	3
Railroad	3
State Parks	15
National Parks	30
Wetlands	15
Urban	15
Slope	0.1-0.8
Base*	1

*Natural gas pipelines as analog (MIT 2006)

SimCCS: Cap and Trade

MINIMIZE

$$\sum_{i\in S}(F_i^s s_i + V_i^s a_i) + \sum_{i\in I}\sum_{j\in N_i}\sum_{d\in D} F_{ijd}^p y_{ijd} + \sum_{i\in I}\sum_{j\in N_i} V_{ij}^p x_{ij} + \sum_{j\in R}(F_j^r r_j + V_j^r b_j)$$

(1) $$x_{ij} - \sum_{d\in D} {}_{\max} Q_{ijd}^p y_{ijd} \le 0 \qquad \forall i \in I,\ j \in N_i$$

(2) $$x_{ij} - \sum_{d\in D} {}_{\min} Q_{ijd}^p y_{ijd} \ge 0 \qquad \forall i \in I,\ j \in N_i$$

(3) $$\sum_{j\in N_i} x_{ij} - \sum_{j\in N_i} x_{ji} - a_i + b_i = 0 \qquad \forall i \in I$$

(4) $$a_i - Q_i^s s_i \le 0 \qquad \forall i \in S$$

(5) $$b_j - Q_j^r r_j \le 0 \qquad \forall j \in R$$

(6) $$\sum_{i\in S} a_i \ge T$$

(7) $$\sum_{d\in D} y_{ijd} \le 1 \qquad \forall i \in I,\ j \in N_i$$

$y_{ijd} \in \{0,1\}$ $\forall i \in I, j \in N_i, d \in D$

$s_i \in \{0,1\}$ $\forall i \in S$

$r_j \in \{0,1\}$ $\forall j \in R$

$x_{ij} \ge 0$ $\forall i, j \in N_i$

$a_i \ge 0$ $\forall j \in S$

$b_j \ge 0$ $\forall j \in R$

Middleton and Bielicki (2009) A scalable infrastructure for carbon capture and storage: ***simCCS***, *Energy Policy, (39), 1052-1060*

SimCCS: Cap and Trade

MINIMIZE **Cost to open source, capture CO_2**

$$+\sum_{i\in I}\sum_{j\in N_i}\sum_{d\in D} F_{ijd}^{p} y_{ijd} + \sum_{i\in I}\sum_{j\in N_i} V_{ij}^{p} x_{ij} + \sum_{j\in R}(F_j^r r_j + V_j^r b_j)$$

(1) $$x_{ij} - \sum_{d\in D} {}_{\max} Q_{ijd}^{p} y_{ijd} \le 0 \qquad \forall i \in I,\ j \in N_i$$

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(5) $$b_j - Q_j^r r_j \le 0 \qquad \forall j \in R$$

(6) $$\sum_{i\in S} a_i \ge T$$

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$$y_{ijd} \in \{0,1\} \quad \forall i \in I,\ j \in N_i,\ d \in D \qquad\qquad x_{ij} \ge 0 \quad \forall i,\ j \in N_i$$

$$s_i \in \{0,1\} \quad \forall i \in S \qquad\qquad a_i \ge 0 \quad \forall j \in S$$

$$r_j \in \{0,1\} \quad \forall j \in R \qquad\qquad b_j \ge 0 \quad \forall j \in R$$

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SimCCS: Cap and Trade

MINIMIZE **Cost to open source, capture CO_2** + **Cost to purchase land, construct pipeline, and transport CO_2** $+ \sum_{j \in R} (F_j^r r_j + V_j^r b_j)$

(1) $x_{ij} - \sum_{d \in D} {}_{\max} Q_{ijd}^p y_{ijd} \le 0 \qquad \forall i \in I, j \in N_i$

(2) $x_{ij} - \sum_{d \in D} {}_{\min} Q_{ijd}^p y_{ijd} \ge 0 \qquad \forall i \in I, j \in N_i$

(3) $\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0 \qquad \forall i \in I$

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(5) $b_j - Q_j^r r_j \le 0 \qquad \forall j \in R$

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$y_{ijd} \in \{0,1\} \quad \forall i \in I, j \in N_i, d \in D$

$s_i \in \{0,1\} \quad \forall i \in S$

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$x_{ij} \ge 0 \quad \forall i, j \in N_i$

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SimCCS: Cap and Trade

MINIMIZE

Cost to open source, capture CO_2 + Cost to purchase land, construct pipeline, and transport CO_2 + Cost to open reservoir, inject CO_2

(1) $$x_{ij} - \sum_{d \in D} {}_{\max} Q^p_{ijd} y_{ijd} \le 0 \qquad \forall i \in I, j \in N_i$$

(2) $$x_{ij} - \sum_{d \in D} {}_{\min} Q^p_{ijd} y_{ijd} \ge 0 \qquad \forall i \in I, j \in N_i$$

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$$s_i \in \{0,1\} \quad \forall i \in S \qquad a_i \ge 0 \quad \forall j \in S$$

$$r_j \in \{0,1\} \quad \forall j \in R \qquad b_j \ge 0 \quad \forall j \in R$$

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SimCCS: Cap and Trade

MINIMIZE

Cost to open source, capture CO_2 + Cost to purchase land, construct pipeline, and transport CO_2 + Cost to open reservoir, inject CO_2

(1)	$x_{ij} - \sum_{d \in D} {}_{\max} Q^p_{ijd} y_{ijd} \le 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be less than maximum pipeline capacity
(2)	$x_{ij} - \sum_{d \in D} {}_{\min} Q^p_{ijd} y_{ijd} \ge 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be more than minimum pipeline capacity
(3)	$\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0$	$\forall i \in I$	CO_2 flow leaving a node must equal inflow
(4)	$a_i - Q^s_i s_i \le 0$	$\forall i \in S$	CO_2 captured at a source must not exceed supply
(5)	$b_j - Q^r_j r_j \le 0$	$\forall j \in R$	CO_2 stored at a sink must not exceed capacity
(6)	$\sum_{i \in S} a_i \ge T$		Target amount of CO_2 to store or sequester
(7)	$\sum_{d \in D} y_{ijd} \le 1$	$\forall i \in I, j \in N_i$	Only one pipeline can be built between nodes

$y_{ijd} \in \{0,1\}$ $\forall i \in I, j \in N_i, d \in D$
$s_i \in \{0,1\}$ $\forall i \in S$
$r_j \in \{0,1\}$ $\forall j \in R$

0,1 constraints

$x_{ij} \ge 0$ $\forall i, j \in N_i$
$a_i \ge 0$ $\forall j \in S$
$b_j \ge 0$ $\forall j \in R$

Non-negativity constraints

Middleton and Bielicki (2009) A scalable infrastructure for carbon capture and storage: *simCCS*, *Energy Policy, (39), 1052-1060*

SimCCS: CO_2 Tax

MINIMIZE

$$\underbrace{\sum_{i\in S}(F_i^s s_i + V_i^s a_i)}_{\text{SOURCE}} + \underbrace{\sum_{i\in I}\sum_{j\in N_i}\sum_{d\in D} F_{ijd}^p y_{ijd} + \sum_{i\in I}\sum_{j\in N_i} V_{ij}^p x_{ij}}_{\text{TRANSPORT}} + \underbrace{\sum_{j\in R}(F_j^r r_j + V_j^r b_j)}_{\text{RESERVOIR}} + \underbrace{\sum_{i\in S} C(Q_i^s - a_i)}_{CO_2\text{ TAX}} - \underbrace{\sum_{j\in R} E_j b_j}_{\text{EOR}}$$

(1)	$x_{ij} - \sum_{d\in D} {}_{\max} Q_{ijd}^p y_{ijd} \le 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be less than maximum pipeline capacity
(2)	$x_{ij} - \sum_{d\in D} {}_{\min} Q_{ijd}^p y_{ijd} \ge 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be more than minimum pipeline capacity
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$s_i \in \{0,1\}$ $\forall i \in S$
$r_j \in \{0,1\}$ $\forall j \in R$

0,1 constraints

$x_{ij} \ge 0$ $\forall i, j \in N_i$
$a_i \ge 0$ $\forall j \in S$
$b_j \ge 0$ $\forall j \in R$

Non-negativity constraints

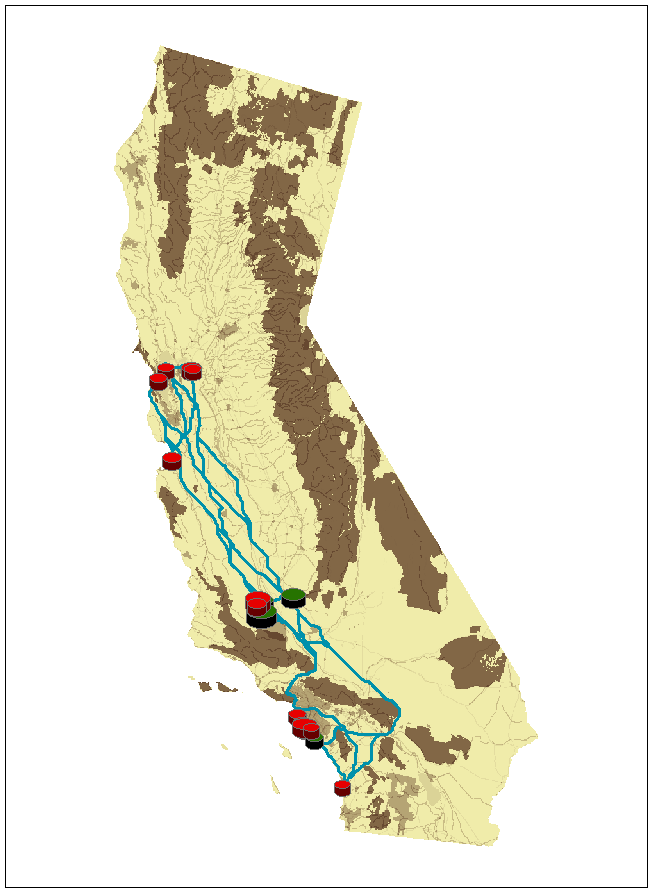
California Infrastructure

12 Potential Sources

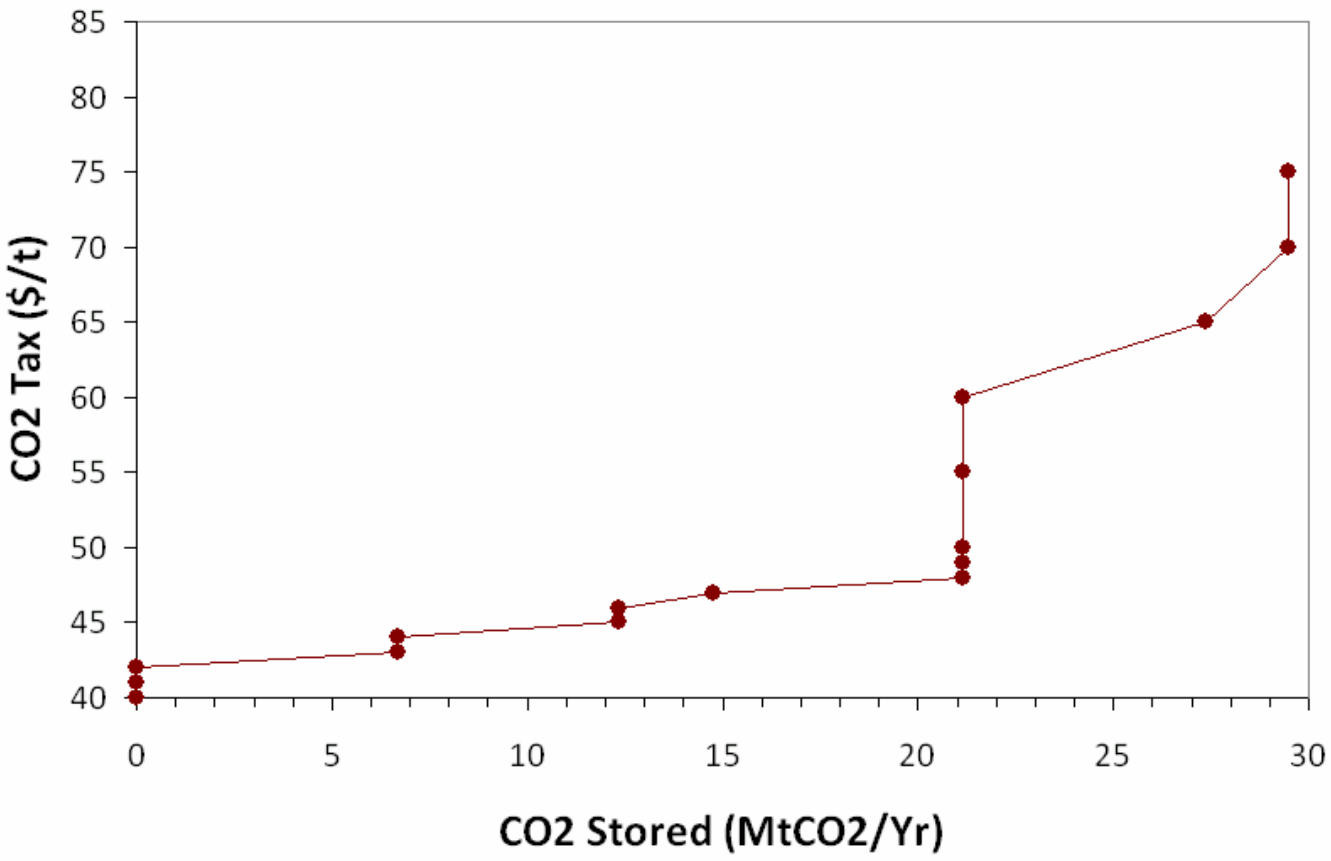
5 Potential Reservoirs

Potential Routes

- *Between every **S**-**R** combination.*
- *Avoid darker patches.*

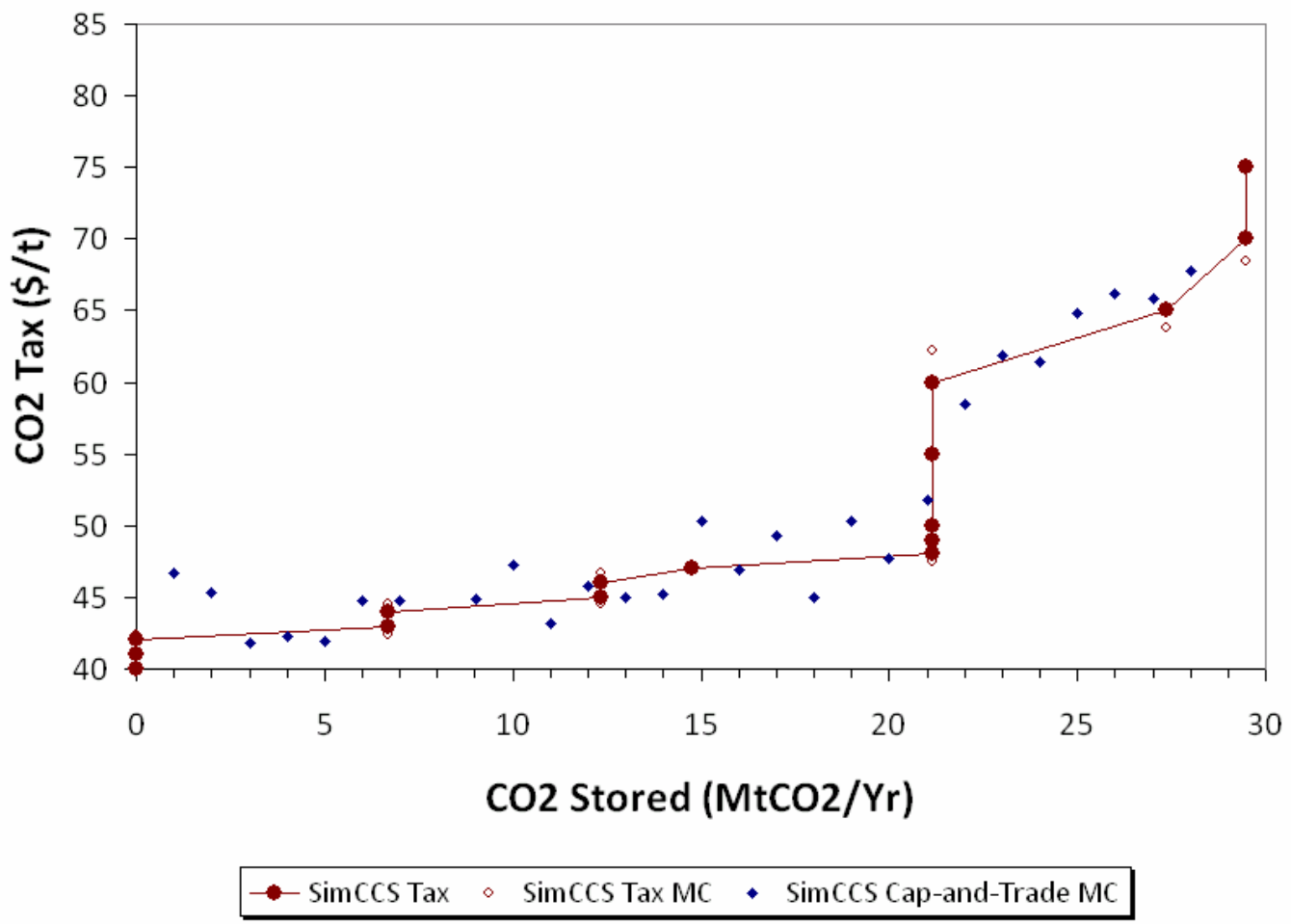


Price of CCS Deployment: S12R5



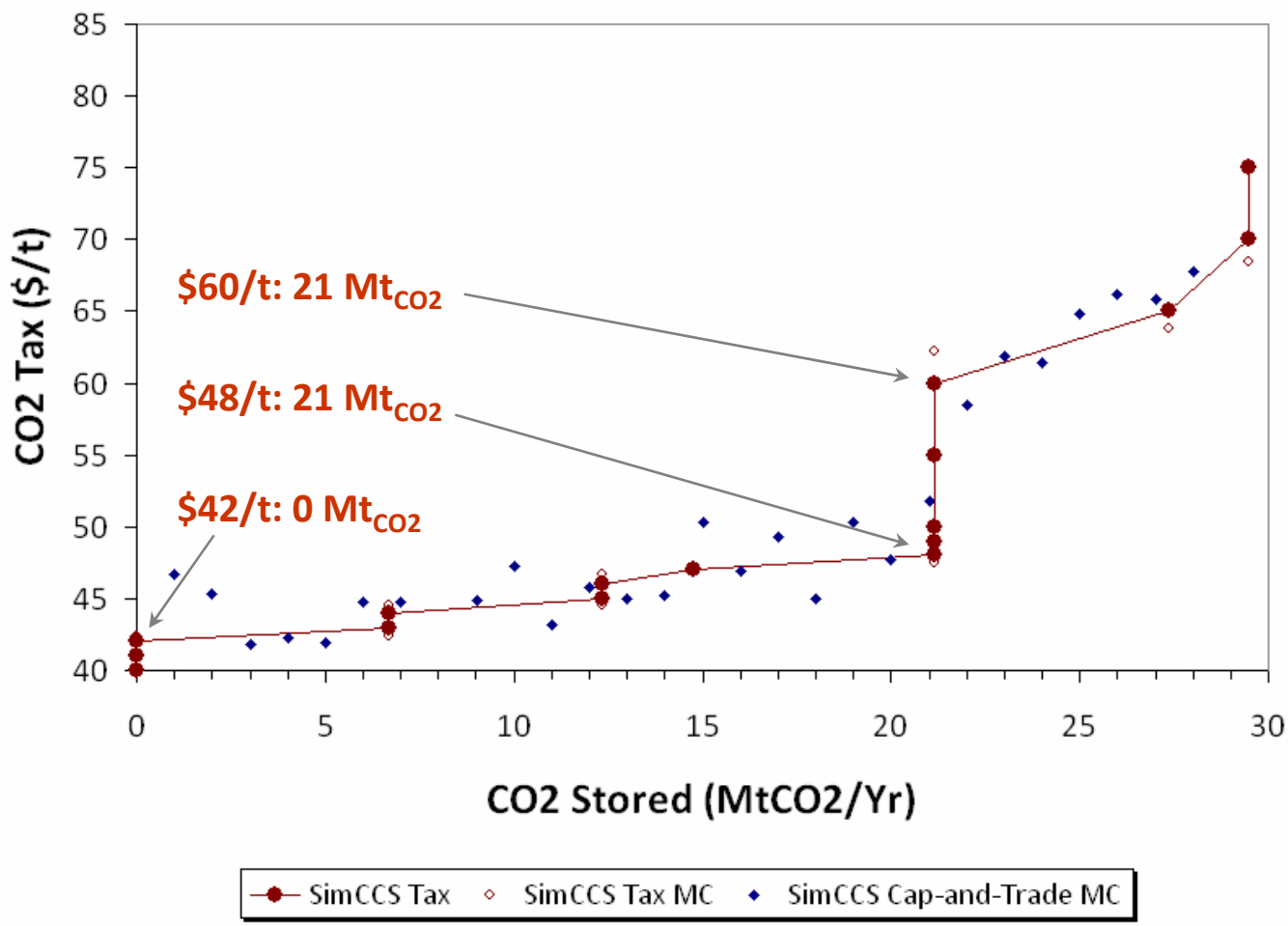
Marginal Costs of CCS Deployment: S12R5

- **Marginal costs should be equivalent between cap-and-trade analysis and CO_2 tax analysis.**



Marginal Gains of CCS Deployment: S12R5

- **$42/t to $48/t: large gain in abatement for $6/t increase.**
- **$48/t to $60/t: no gain in abatement for $12/t increase.**



Summary

- CCS is a spatial coupling of sources and reservoirs.
- CCS needs an economic incentive to be deployed.
- Infrastructure deployment is not always sensitive to CO_2 price.
- Some CO_2 prices are "better" than others.
- Some increments in CO_2 prices yield much more abatement than other increments.

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  - Shell Production and Exploration
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  - The Energy Foundation
  - Los Alamos National Laboratory
  - Zero Emissions Research and Technology Center Collaborative

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