

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



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# Carbon Capture and Storage

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CCS

*Spatial*

*Technological*

*Scale*

PREVIEW

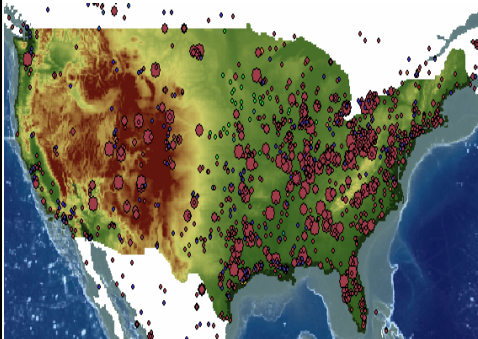

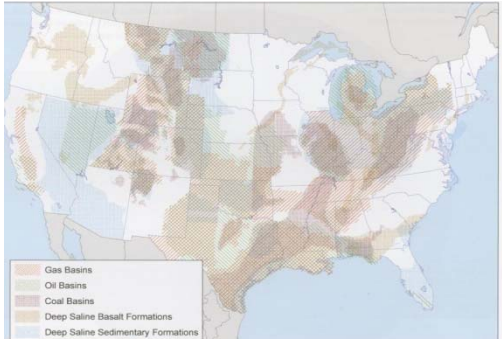
Economic  
Incentives

SimCCS  
MODEL

DEPLOYMENT

SUMMARY

THANK YOU

Point Sources <sup>1</sup>	Pipeline Infrastructure <sup>2</sup>	Injection Reservoirs <sup>3</sup>
		
<b>Known</b>	<b>Unknown</b>	<b>Unknown</b>

# Carbon Capture and Storage

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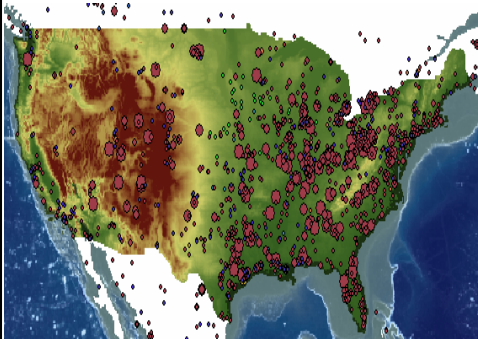

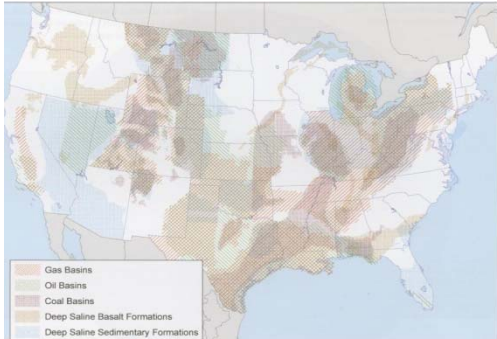
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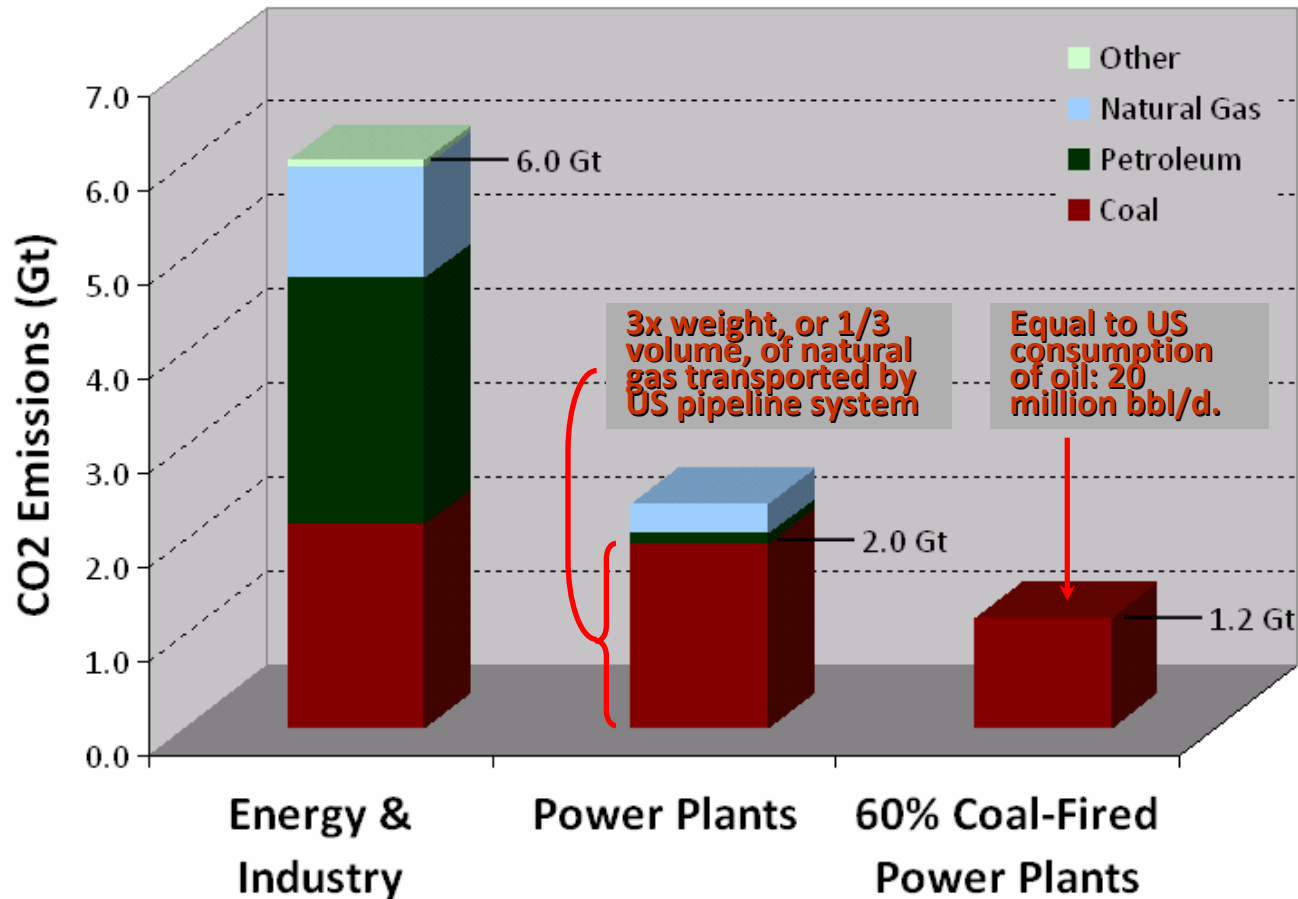
Point Sources <sup>1</sup>	Pipeline Infrastructure <sup>2</sup>	Injection Reservoirs <sup>3</sup>
		
Known	Unknown	Unknown

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

<sup>1</sup>NETL (2007), <sup>2</sup>PHMSA (2003), <sup>3</sup>Dooley et al. (2006)

# Magnitude of CO<sub>2</sub> Production<sup>1</sup>

## United States (2005)



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

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- An economic incentive will be necessary for CCS to be deployed.
- Introduce a model that spatially deploys integrated CCS systems based on CO<sub>2</sub> price.
- *Marginal* deployment varies with price level.
- Suggest “better” CO<sub>2</sub> prices.

# Market-Based Mechanisms

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## 1. Cap-and-Trade Permit System

- Set quantity, market determines price.
- Price volatility

## 2. Tax on CO<sub>2</sub> 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<sub>2</sub> tax in context of climate change.*

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

# Scalable Infrastructure Model for CCS: *SimCCS*<sup>1</sup>

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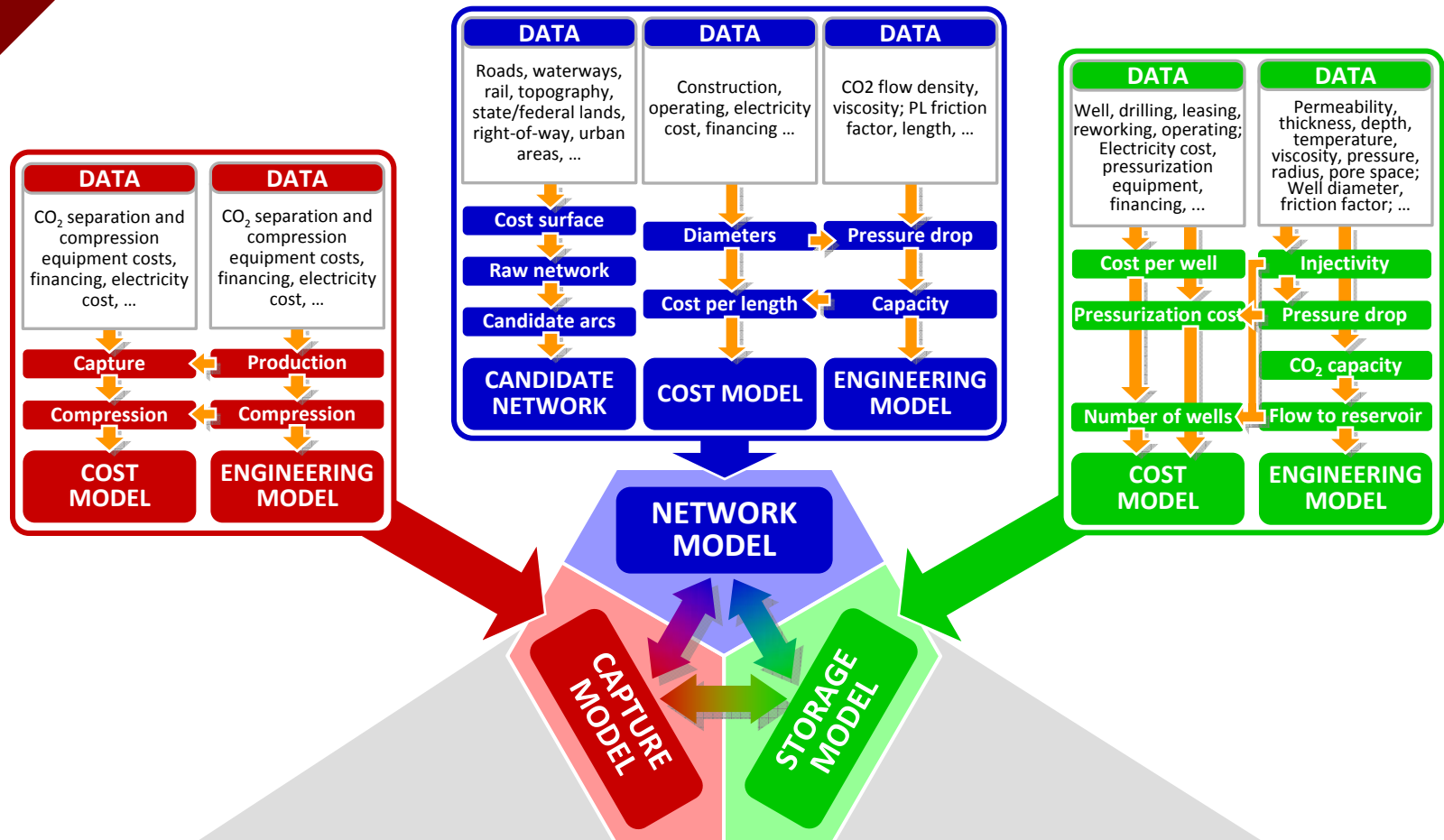
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COSTS	SPATIAL DEPLOYMENT	CO <sub>2</sub> FLOWS	GENERAL
Cost to deploy CCS infrastructure	Where to capture and/or release CO <sub>2</sub>	CO <sub>2</sub> amount to be captured at each source	Amount of CO <sub>2</sub> cost-effectively sequestered
Capture, transport, and storage costs	Location of capture-ready CO <sub>2</sub> sources	How much CO <sub>2</sub> should be stored in each reservoir	Scale of CCS infrastructure
Carbon tax (\$/tonne)	Which reservoirs should inject/store CO <sub>2</sub>	CO <sub>2</sub> pipeline capacities	Policy implications
Cap and trade pricing	Dedicated CO <sub>2</sub> pipeline network	CO <sub>2</sub> allocation between sources and reservoirs	Tradeoff between capture, transport, and storage

<sup>1</sup>Middleton and Bielicki (2009a, 2009b), Bielicki (2008c)



# CCS Problem Components

**Simultaneously and optimally decide:**

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

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COSTS	SPATIAL DEPLOYMENT	CO <sub>2</sub> FLOWS	GENERAL
CO <sub>2</sub> separation and compression	Where to capture and/or release CO <sub>2</sub>	CO <sub>2</sub> amount to be captured at each source	CO <sub>2</sub> capture applications
CO <sub>2</sub> transport	Location of capture-ready CO <sub>2</sub> sources	How much CO <sub>2</sub> should be stored in each reservoir	CO <sub>2</sub> storage applications
Carbon tax	Which reservoirs should inject/store CO <sub>2</sub>	CO <sub>2</sub> pipeline capacities	CO <sub>2</sub> capture and storage applications
Cap and trade pricing	Dedicated CO <sub>2</sub> pipeline <i>network</i>	CO <sub>2</sub> allocation between sources and reservoirs	CO <sub>2</sub> capture and storage applications

# SimCCS: Engineering Economic Models

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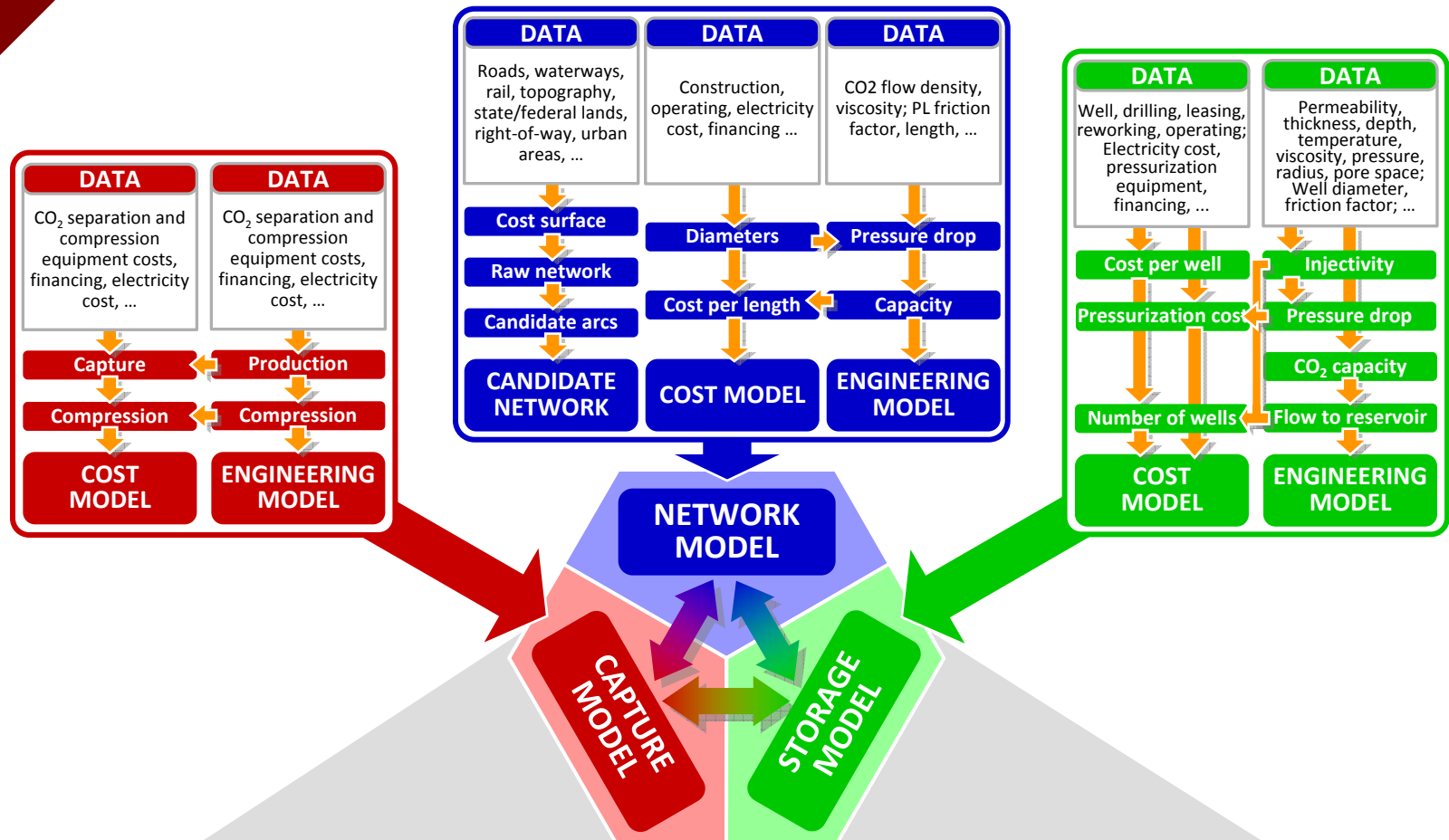
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## Integrated coupling of technologies and geologies:

- 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

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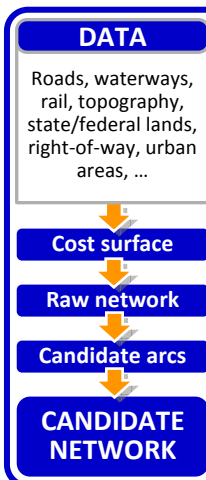
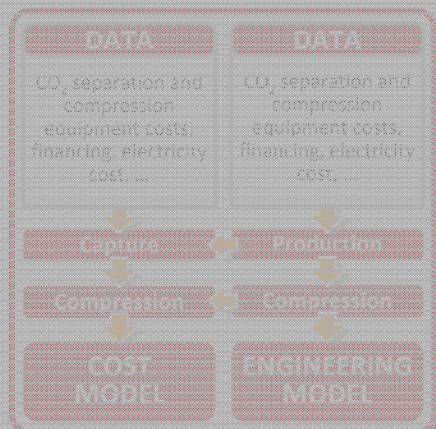
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## Innovation in Geospatial Optimization:

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

## Pipelines:<sup>1</sup>

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

## Reservoirs:<sup>1</sup>

- Geologic parameters and conditions

## Sources:

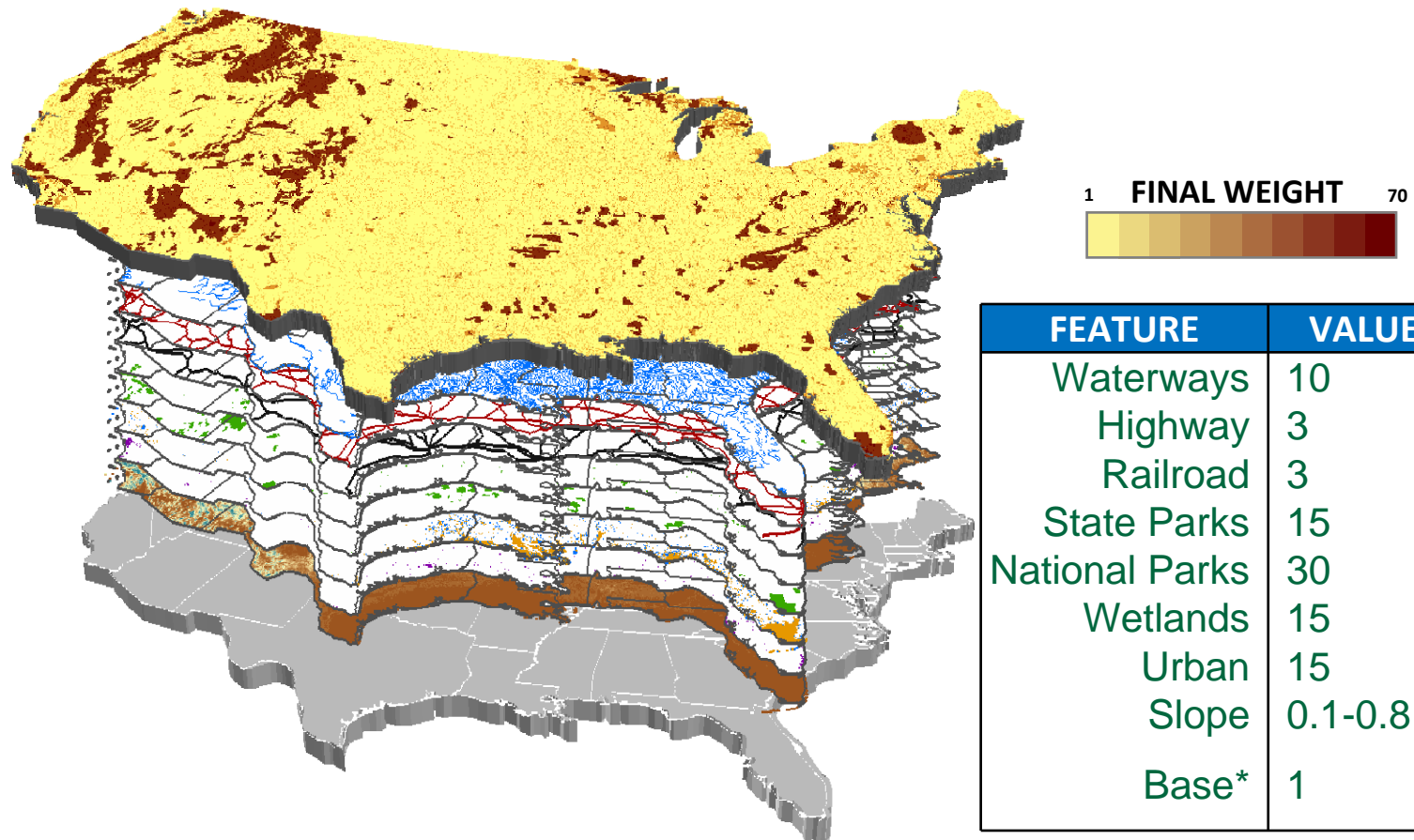
- Adjusted from literature review (IPCC, 2005)
- Compression/pressurization equipment (IEAGHG 2002)

Includes relevant CO<sub>2</sub> properties  
Basic thermodynamics, fluid mechanics, etc.

<sup>1</sup>Bielicki (2008)

# Routing Pipelines

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



\*Natural gas pipelines as analog (MIT 2006)

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# SimCCS: Cap and Trade

MINIMIZE

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

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

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

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

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

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

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

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

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

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

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

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

$$a_i \geq 0 \quad \forall i \in S$$

$$b_j \geq 0 \quad \forall j \in R$$

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<sub>2</sub>

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

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

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

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

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$$b_j \geq 0 \quad \forall j \in R$$

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# SimCCS: Cap and Trade

MINIMIZE

Cost to open source, capture CO<sub>2</sub>

+

Cost to purchase land, construct pipeline, and transport CO<sub>2</sub>

$$+ \sum_{j \in R} (F_j^r r_j + V_j^r b_j)$$

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

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

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

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# SimCCS: Cap and Trade

MINIMIZE

Cost to open source, capture CO<sub>2</sub>

+

Cost to purchase land, construct pipeline, and transport CO<sub>2</sub>

+

Cost to open reservoir, inject CO<sub>2</sub>

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

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

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# SimCCS: Cap and Trade

MINIMIZE

Cost to open source, capture CO<sub>2</sub>

+

Cost to purchase land, construct pipeline, and transport CO<sub>2</sub>

+

Cost to open reservoir, inject CO<sub>2</sub>

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$$(1) \quad x_{ij} - \sum_{d \in D} \max Q_{ijd}^p y_{ijd} \leq 0$$

$$\forall i \in I, j \in N_i$$

CO<sub>2</sub> flow must be less than maximum pipeline capacity

$$(2) \quad x_{ij} - \sum_{d \in D} \min Q_{ijd}^p y_{ijd} \geq 0$$

$$\forall i \in I, j \in N_i$$

CO<sub>2</sub> flow must be more than minimum pipeline capacity

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

$$\forall i \in I$$

CO<sub>2</sub> flow leaving a node must equal inflow

$$(4) \quad a_i - Q_i^s s_i \leq 0$$

$$\forall i \in S$$

CO<sub>2</sub> captured at a source must not exceed supply

$$(5) \quad b_j - Q_j^r r_j \leq 0$$

$$\forall j \in R$$

CO<sub>2</sub> stored at a sink must not exceed capacity

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

Target amount of CO<sub>2</sub> to store or sequester

$$(7) \quad \sum_{d \in D} y_{ijd} \leq 1$$

$$\forall i \in I, j \in N_i$$

Only one pipeline can be built between nodes

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

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

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

0,1 constraints

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

$$a_i \geq 0 \quad \forall i \in S$$

$$b_j \geq 0 \quad \forall j \in R$$

Non-negativity constraints

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

# SimCCS: CO<sub>2</sub> Tax

MINIMIZE

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

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

$\forall i \in I, j \in N_i$

CO<sub>2</sub> flow must be less than maximum pipeline capacity

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

$\forall i \in I, j \in N_i$

CO<sub>2</sub> flow must be more than minimum pipeline capacity

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

$\forall i \in I$

CO<sub>2</sub> flow leaving a node must equal inflow

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

$\forall i \in S$

CO<sub>2</sub> captured at a source must not exceed supply

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

$\forall j \in R$

CO<sub>2</sub> stored at a sink must not exceed capacity

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

Target amount of CO<sub>2</sub> to store or sequester

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

$\forall i \in I, j \in N_i$

Only one pipeline can be built between nodes

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

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

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

0,1 constraints

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

$a_i \geq 0 \quad \forall j \in S$

$b_j \geq 0 \quad \forall j \in R$

Non-negativity constraints

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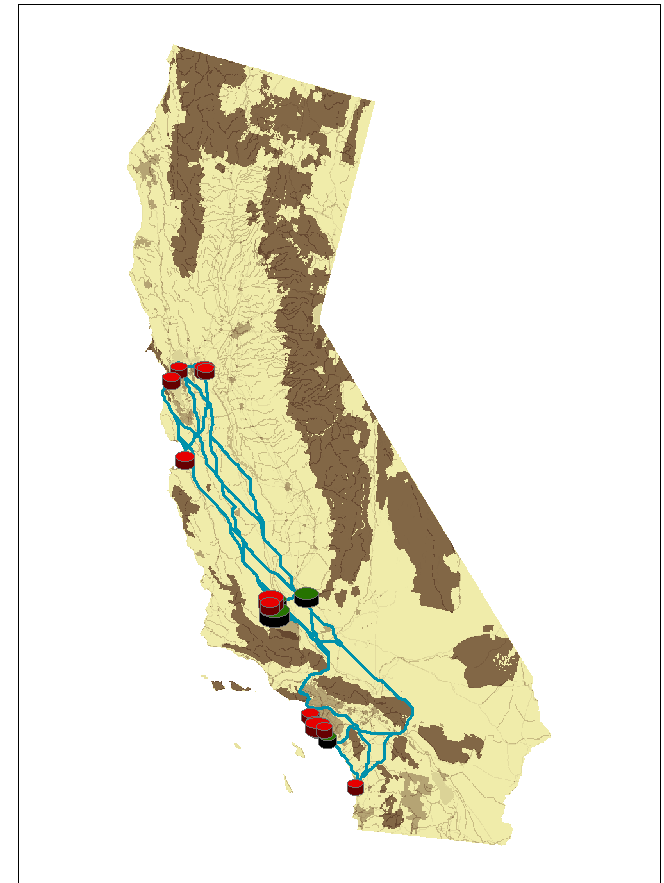
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## 12 Potential Sources

## 5 Potential Reservoirs

## Potential Routes

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



# Price of CCS Deployment: S12R5

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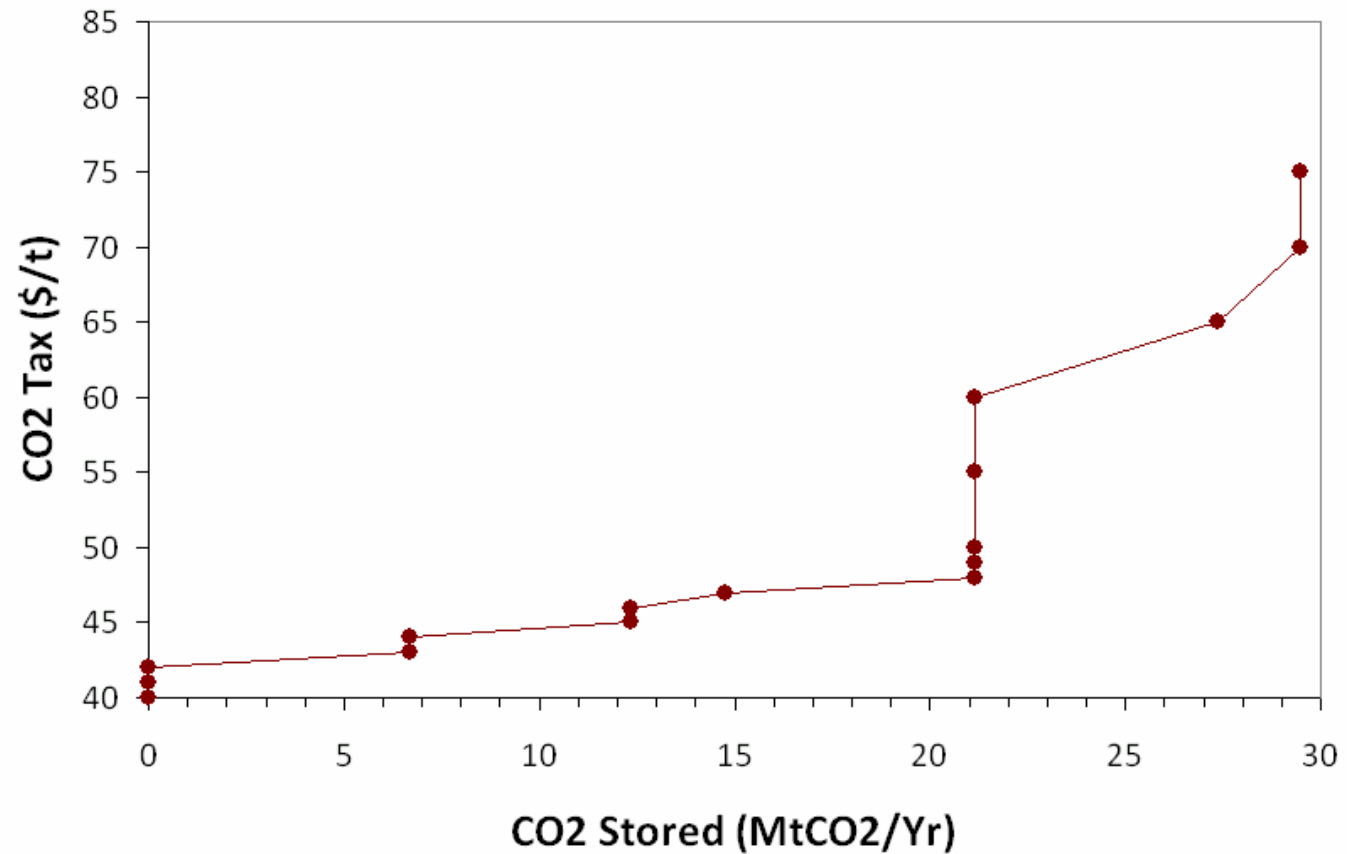
Price vs. Quantity

Verify

Gains

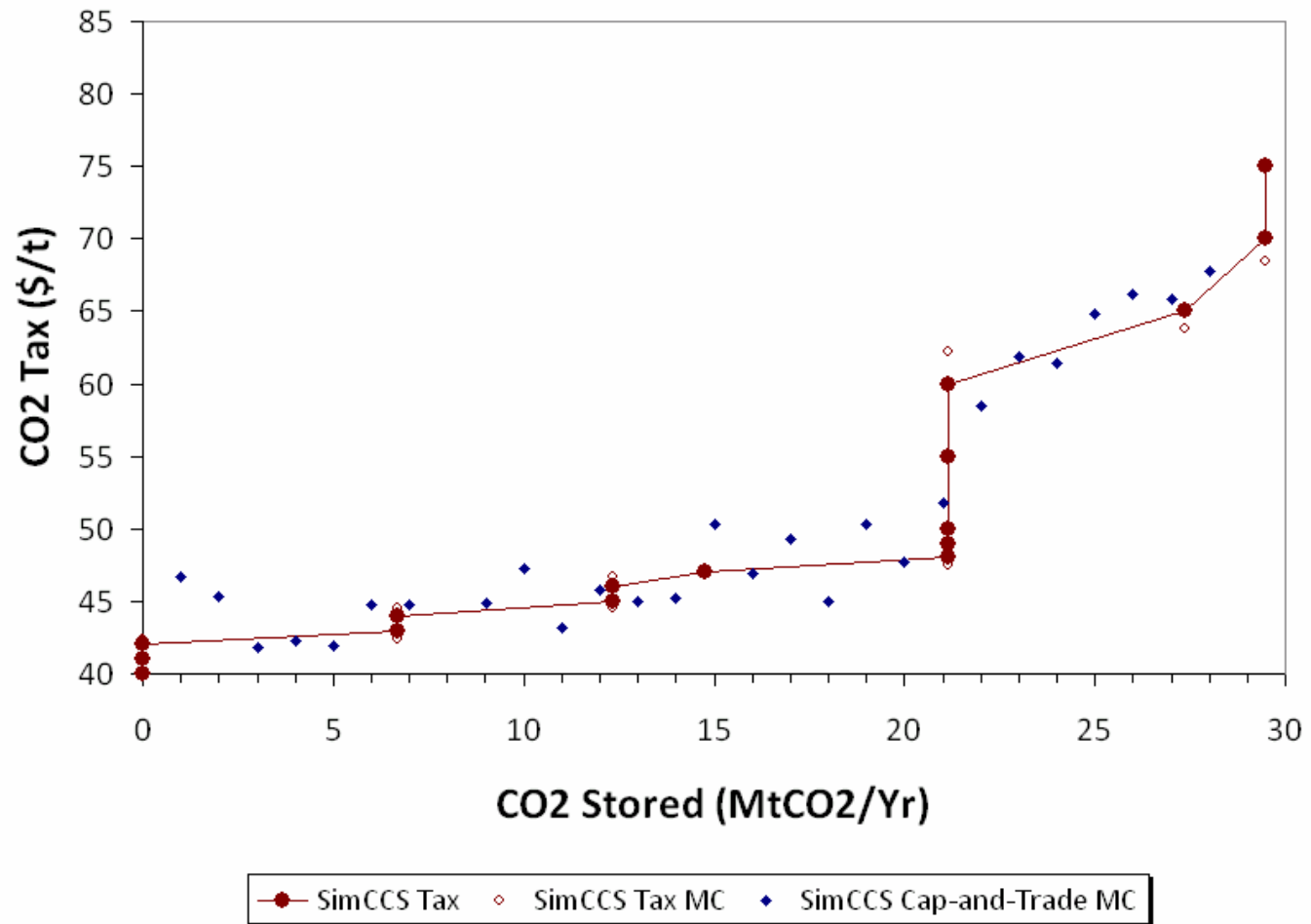
SUMMARY

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# Marginal Costs of CCS Deployment: S12R5

- Marginal costs should be equivalent between cap-and-trade analysis and CO<sub>2</sub> tax analysis.



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Price vs. Quantity

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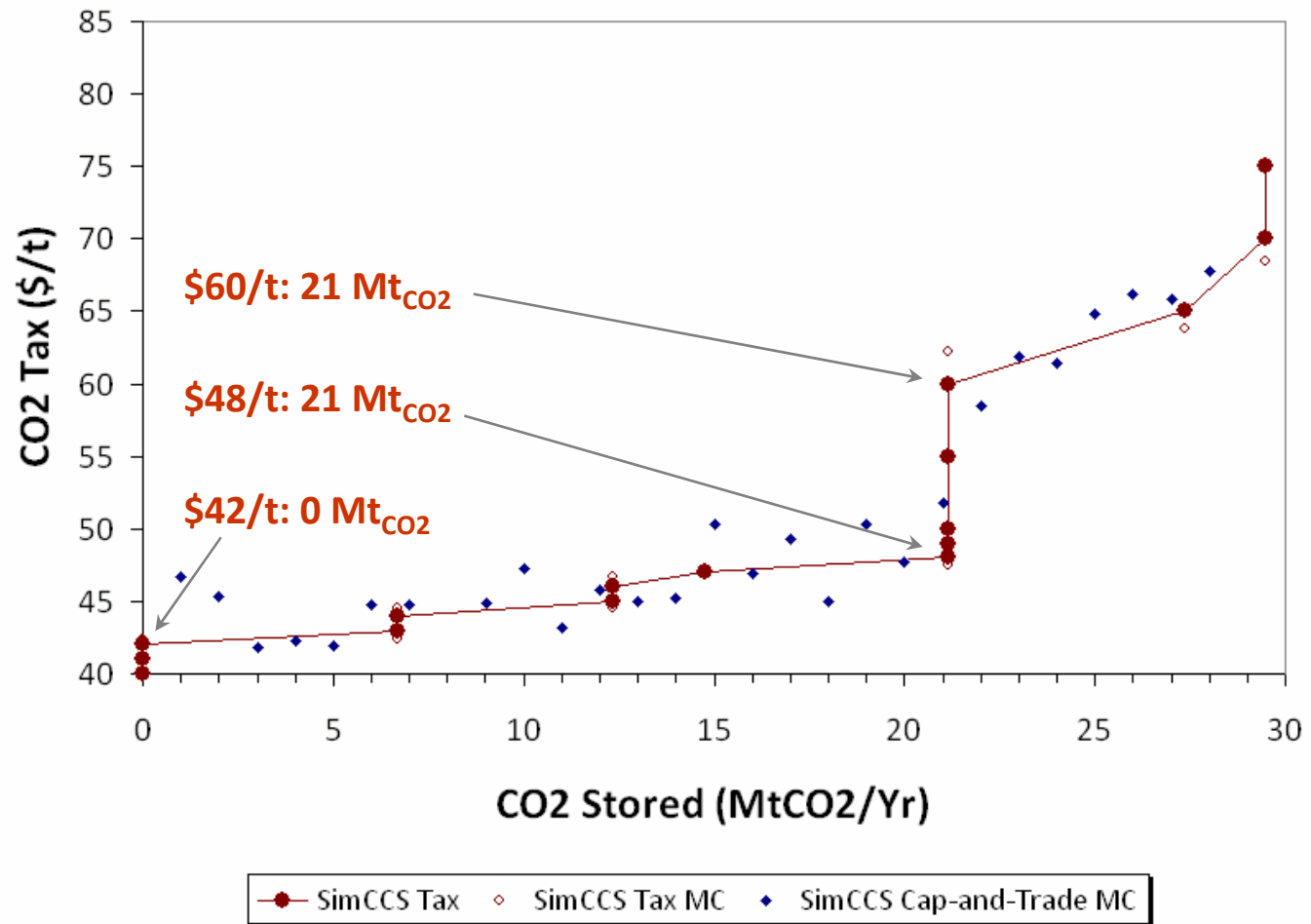
Gains

SUMMARY

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# 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.



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Price vs. Quantity

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Gains

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# 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<sub>2</sub> price.
- Some CO<sub>2</sub> prices are “better” than others.
- Some increments in CO<sub>2</sub> prices yield much more abatement than other increments.

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