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

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Spatial Deployment of CCS with CO₂ - Kuby, Bielicki, Middleton

<table>
<thead>
<tr>
<th>Point Sources¹</th>
<th>Pipeline Infrastructure²</th>
<th>Injection Reservoirs³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

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 CO₂ Production

United States (2005)

- Energy & Industry: 6.0 Gt
- Power Plants: 2.0 Gt
- 60% Coal-Fired Power Plants: 1.2 Gt

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

- 3x weight, or 1/3 volume, of natural gas transported by US pipeline system
- Equal to US consumption of oil: 20 million bbl/d.
• 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.
1. **Cap-and-Trade Permit System**
   - Set quantity, market determines price.
   - Price volatility

2. **Tax on CO₂ Emissions**
   - Set price, market determines quantity.
   - Quantity volatility

3. **Optimal: Hybrid, cap-and-trade with price “safety valve.”**
   - Limit maximum price to reduce volatility
   - *More like a CO₂ tax in context of climate change.*

### Permits vs. Taxes

<table>
<thead>
<tr>
<th>Economic optimality:</th>
<th>Optimal if certain about quantity</th>
<th>Optimal if certain about cost per tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Political economy:</td>
<td>More risks for distributional effects</td>
<td>More risks for efficiency effects</td>
</tr>
<tr>
<td></td>
<td>Probably more politically tenable</td>
<td>Probably simpler to implement</td>
</tr>
</tbody>
</table>
Scalable Infrastructure Model for CCS: SimCCS

**COSTS**
- Cost to deploy CCS infrastructure
- Capture, transport, and storage costs
- Carbon tax ($/tonne)
- Cap and trade pricing

**SPATIAL DEPLOYMENT**
- Where to capture and/or release CO₂
- Location of capture-ready CO₂ sources
- Dedicated CO₂ pipeline network

**CO₂ FLOWS**
- CO₂ amount to be captured at each source
- How much CO₂ should be stored in each reservoir
- CO₂ pipeline capacities
- CO₂ allocation between sources and reservoirs

**GENERAL**
- Amount of CO₂ cost-effectively sequestered
- Scale of CCS infrastructure
- Policy implications
- Tradeoff between capture, transport, and storage

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**DATA**
- Roads, waterways, rail, topography, state/federal lands, right-of-way, urban areas, ...
- Construction, operating, electricity costs, financing ...
- CO₂ flow density, viscosity, PL friction factor, length, ...
- Well, drilling, leasing, reworking, operating; Electricity cost, pressurization equipment, financing, ...
- Permeability, thickness, depth, temperature, viscosity, pressure, radius, pore space; Well diameter, friction factor; ...

**ENGINEERING MODEL**
- Cost surface
- Diameters
- Pressure drop
- Cost per well
- Injectivity
- Pressurization cost
- Pressure drop
- CO₂ capacity
- Number of wells
- Flow to reservoir

**NETWORK MODEL**
- Captures
- Production
- Compression
- Candidate arcs
- Cost per length
- Capacity
- Raw network
- Pressurization cost
- Electric cost, pressurization equipment, financing, ...

**CANDIDATE NETWORK**
- COST MODEL
- ENGINEERING MODEL

---

DOE-NETL 05/09

CCS

PREVIEW

Economic Incentives

SimCCS MODEL
- Approach
- Methodology
- Example

DEPLOYMENT

SUMMARY

THANK YOU

1Middleton and Bielicki (2009a, 2009b), Bielicki (2008c)
Simultaneously and optimally decide:

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

**Spatial Deployment**

- Where to capture and/or release CO\textsubscript{2}
- Location of capture-ready CO\textsubscript{2} sources
- Which reservoirs should inject/store CO\textsubscript{2}
- Dedicated CO\textsubscript{2} pipeline network

**CO\textsubscript{2} Flows**

- CO\textsubscript{2} amount to be captured at each source
- How much CO\textsubscript{2} should be stored in each reservoir
- CO\textsubscript{2} pipeline capacities
- CO\textsubscript{2} allocation between sources and reservoirs

**General**

- Cost of CCS infrastructure
- Cost to deploy CCS infrastructure
- CO\textsubscript{2} pipeline capacities
- CO\textsubscript{2} allocation between sources and reservoirs

**Economic Incentives**

- DOE-NETL 05/09
- CCS PREVIEW
- SimCCS Model
  - Approach
  - Methodology
  - Example

DEPLOYMENT

SUMMARY

THANK YOU
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

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

Includes relevant CO₂ properties
- Basic thermodynamics, fluid mechanics, etc.

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

Reservoirs:
- Geologic parameters and conditions

1Bielicki (2008)
• Shortest path algorithm incorporates social and physical topography:
  • Relative cost of routing through cell (1km x 1km)

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterways</td>
<td>10</td>
</tr>
<tr>
<td>Highway</td>
<td>3</td>
</tr>
<tr>
<td>Railroad</td>
<td>3</td>
</tr>
<tr>
<td>State Parks</td>
<td>15</td>
</tr>
<tr>
<td>National Parks</td>
<td>30</td>
</tr>
<tr>
<td>Wetlands</td>
<td>15</td>
</tr>
<tr>
<td>Urban Slope</td>
<td>15</td>
</tr>
<tr>
<td>Base*</td>
<td>0.1-0.8</td>
</tr>
</tbody>
</table>

*Natural gas pipelines as analog (MIT 2006)
SimCCS: Cap and Trade

\[
\sum_{i \in S} (F^s_i s_i + V^s_i a_i) + \sum_{i \in I} \sum_{j \in N_i} \sum_{d \in D} F^p_{ijd} x_{ijd} + \sum_{i \in I} \sum_{j \in N_i} V^p_{ij} x_{ij} + \sum_{j \in R} (F^r_j r_j + V^r_j b_j)
\]

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

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

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

(4) \( a_i - Q^s_i s_i \leq 0 \quad \forall i \in S \)

(5) \( b_j - Q^r_j r_j \leq 0 \quad \forall j \in R \)

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

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

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

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

\( a_i \geq 0 \quad \forall i \in S \)

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

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

\( b_j \geq 0 \quad \forall j \in R \)


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SimCCS: Cap and Trade

\[ \text{MINIMIZE} \quad \sum_{i \in I} \sum_{j \in N_i} \sum_{d \in D} F_{ijd} y_{ijd} + \sum_{i \in I} \sum_{j \in N_i} V_{ij} x_{ij} + \sum_{j \in R} (F_j r_j + V_j b_j) \]

\begin{align*}
(1) \quad & x_{ij} - \max_{d \in D} Q_{ijd} y_{ijd} \leq 0 & \forall i \in I, j \in N_i \\
(2) \quad & x_{ij} - \min_{d \in D} Q_{ijd} y_{ijd} \geq 0 & \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 & \forall i \in I \\
(4) \quad & a_i - Q_i^s s_i \leq 0 & \forall i \in S \\
(5) \quad & b_j - Q_j^r r_j \leq 0 & \forall j \in R \\
(6) \quad & \sum_{i \in S} a_i \geq T \\
(7) \quad & \sum_{d \in D} y_{ijd} \leq 1 & \forall i \in I, j \in N_i
\end{align*}

\[ y_{ijd} \in \{0,1\} \quad \forall i \in I, j \in N_i, d \in D \]
\[ x_{ij} \geq 0 \quad \forall i, j \in N_i \]
\[ s_i \in \{0,1\} \quad \forall i \in S \]
\[ a_i \geq 0 \quad \forall j \in S \]
\[ r_j \in \{0,1\} \quad \forall j \in R \]
\[ b_j \geq 0 \quad \forall j \in R \]

**SimCCS: Cap and Trade**

**Cost to open source, capture CO₂** + **Cost to purchase land, construct pipeline, and transport CO₂** + $\sum_{j \in R} (F_j^r r_j + V_j^r b_j)$

1. $x_{ij} - \sum_{d \in D} \max D Q_{ijd} y_{ijd} \leq 0 \quad \forall i \in I, j \in N_i$
2. $x_{ij} - \sum_{d \in D} \min D Q_{ijd} y_{ijd} \geq 0 \quad \forall i \in I, j \in N_i$
3. $\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0 \quad \forall i \in I$
4. $a_i - Q_i^s s_i \leq 0 \quad \forall i \in S$
5. $b_j - Q_j^r r_j \leq 0 \quad \forall j \in R$
6. $\sum_{i \in S} a_i \geq T$
7. $\sum_{d \in D} y_{ijd} \leq 1 \quad \forall i \in I, j \in N_i$

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

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

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

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

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

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

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

Spatial Deployment of CCS with CO₂ Price – Kuby, Bielicki, Middleton
**SimCCS**: Cap and Trade

<table>
<thead>
<tr>
<th><strong>SimCCS Model</strong></th>
<th><strong>Approach</strong></th>
<th><strong>Methodology</strong></th>
<th><strong>Example</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOE-NETL 05/09</strong></td>
<td>CCS PREVIEW</td>
<td>Economic Incentives</td>
<td>DEPLOYMENT</td>
</tr>
<tr>
<td><strong>SUMMARY</strong></td>
<td><strong>THANK YOU</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Constraints

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) $x_{ij} - \sum_{d \in D} \max Q_{ijd} y_{ijd} \leq 0$</td>
<td>Cost to open source, capture CO₂</td>
</tr>
<tr>
<td>(2) $x_{ij} - \sum_{d \in D} \min Q_{ijd} y_{ijd} \geq 0$</td>
<td>Cost to purchase land, construct pipeline, and transport CO₂</td>
</tr>
<tr>
<td>(3) $\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0$</td>
<td>Cost to open reservoir, inject CO₂</td>
</tr>
<tr>
<td>(4) $a_i - Q_i^s s_i \leq 0$</td>
<td></td>
</tr>
<tr>
<td>(5) $b_j - Q_j^r r_j \leq 0$</td>
<td></td>
</tr>
<tr>
<td>(6) $\sum_{i \in S} a_i \geq T$</td>
<td></td>
</tr>
<tr>
<td>(7) $\sum_{d \in D} y_{ijd} \leq 1$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{ijd}$</td>
<td>${0,1}$</td>
</tr>
<tr>
<td>$s_i$</td>
<td>${0,1}$</td>
</tr>
<tr>
<td>$r_j$</td>
<td>${0,1}$</td>
</tr>
<tr>
<td>$x_{ij}$</td>
<td>${0}$</td>
</tr>
<tr>
<td>$a_i$</td>
<td>${0}$</td>
</tr>
<tr>
<td>$b_j$</td>
<td>${0}$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Cost to open source, capture CO₂</th>
<th>Cost to purchase land, construct pipeline, and transport CO₂</th>
<th>Cost to open reservoir, inject CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x_{ij} - \sum_{d \in D} \max Q^p_{ijd} y_{ijd} \leq 0 ) &amp; ( \forall i \in I, j \in N_i )</td>
<td>( \text{CO}_2 \text{ flow must be less than maximum pipeline capacity} )</td>
<td></td>
</tr>
<tr>
<td>( x_{ij} - \sum_{d \in D} \min Q^p_{ijd} y_{ijd} \geq 0 ) &amp; ( \forall i \in I, j \in N_i )</td>
<td>( \text{CO}_2 \text{ flow must be more than minimum pipeline capacity} )</td>
<td></td>
</tr>
<tr>
<td>( \sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0 ) &amp; ( \forall i \in I )</td>
<td>( \text{CO}_2 \text{ flow leaving a node must equal inflow} )</td>
<td></td>
</tr>
<tr>
<td>( a_i - Q_i^s s_i \leq 0 ) &amp; ( \forall i \in S )</td>
<td>( \text{CO}_2 \text{ captured at a source must not exceed supply} )</td>
<td></td>
</tr>
<tr>
<td>( b_j - Q_j^r r_j \leq 0 ) &amp; ( \forall j \in R )</td>
<td>( \text{CO}_2 \text{ stored at a sink must not exceed capacity} )</td>
<td></td>
</tr>
<tr>
<td>( \sum_{i \in S} a_i \geq T ) &amp; ( \forall i \in I, j \in N_i )</td>
<td>( \text{Target amount of CO}_2 \text{ to store or sequester} )</td>
<td></td>
</tr>
<tr>
<td>( \sum_{d \in D} y_{ijd} \leq 1 ) &amp; ( \forall i \in I, j \in N_i )</td>
<td>( \text{Only one pipeline can be built between nodes} )</td>
<td></td>
</tr>
</tbody>
</table>

\( y_{ijd} \in \{0,1\} \) & \( \forall i \in I, j \in N_i, d \in D \) & \( \text{0,1 constraints} \)

\( s_i \in \{0,1\} \) & \( \forall i \in S \) & \( x_{ij} \geq 0 \) & \( \forall i, j \in N_i \) & \( \text{Non-negativity constraints} \)

\( r_j \in \{0,1\} \) & \( \forall j \in R \) & \( a_i \geq 0 \) & \( \forall j \in S \)

\( b_j \geq 0 \) & \( \forall j \in R \)

**Middleton and Bielicki (2009)** A scalable infrastructure for carbon capture and storage: *SimCCS, Energy Policy*, (39), 1052-1060
**SimCCS:** CO\textsubscript{2} Tax

### Objective Functions

**SOURCE**

\[
\sum_{i \in S} (F_i s_i + V_i a_i)
\]

**TRANSPORT**

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

**RESERVOIR**

\[
\sum_{i \in S} (C_i - a_i) - \sum_{j \in R} E_j b_j
\]

### Constraints

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

### Variables

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

### 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

- \(0,1\) constraints

---

Spatial Deployment of CCS with CO\textsubscript{2}, Price – Kuby, Bielicki, Middleton
12 Potential Sources

5 Potential Reservoirs

Potential Routes

• Between every S-R combination.
• Avoid darker patches.
Price of CCS Deployment: S12R5

- CO2 Tax ($/t) vs. CO2 Stored (MtCO2/Yr)

- Economic Incentives

- SimCCS Model DEPLOYMENT

- Price vs. Quantity

- Verify Gains

- SUMMARY

- THANK YOU
Marginal costs should be equivalent between cap-and-trade analysis and CO₂ tax analysis.

![Graph showing CO₂ Tax vs. CO₂ Stored (MtCO₂/Yr)]
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 CO₂ price.
• Some CO₂ prices are “better” than others.
• Some increments in CO₂ prices yield much more abatement than other increments.
• **Funding**
  • Shell Production and Exploration
  • BP Alternative Energy
  • BP Climate Mitigation Initiative
  • The Energy Foundation
  • Los Alamos National Laboratory
  • Zero Emissions Research and Technology Center Collaborative
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Energy and Transportation Sciences Division | Oak Ridge National Laboratory