Envisioning $\text{CO}_2$ Distribution Networks for CCS in the United States: Modeling $\text{CO}_2$ Pipeline Deployment at a Regional Scale

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Introduction

Overview

- **Objectives:**
  - Model how CCS infrastructure might develop in a large geographic region
  - Develop CO$_2$ abatement cost curve

- **Model:** Mixed integer linear programming model that minimizes CCS deployment costs based on:
  - Estimated costs for capture, transport and injection
  - Regional storage capacity
  - Spatial proximity of sources and sinks
  - Level of CCS deployment
Introduction

The Study Area

- Wyoming
- Utah
- Colorado
- Arizona
- New Mexico
- Texas

Summary Statistics

- Total CO₂ Emissions: 486.6 Mt/yr
- 80% Reduction (50 years): 19.5 Gt
- Total Storage Capacity (Base): 527 Gt
- Total Storage Capacity (Low): 71 Gt
## Capture and Injection Costs

<table>
<thead>
<tr>
<th>Capture Costs</th>
<th>Size Range (MtCO₂ captured/yr)</th>
<th>$/tCO₂ avoided</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Power</td>
<td>1.1 to 19.5</td>
<td>27 to 52</td>
</tr>
<tr>
<td>NGCC Power</td>
<td>0.1 to 2.9</td>
<td>29 to 259</td>
</tr>
<tr>
<td>Refinery</td>
<td>0.1 to 2.5</td>
<td>105 to 223</td>
</tr>
<tr>
<td>Cement</td>
<td>0.1 to 2.6</td>
<td>109 to 180</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.02 to 0.5</td>
<td>20 to 82</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.04 to 0.15</td>
<td>49 to 58</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injection Costs</th>
<th>$/tCO₂ Avoided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline Aquifer</td>
<td>5</td>
</tr>
<tr>
<td>Depleted Oil and Gas</td>
<td>5</td>
</tr>
<tr>
<td>Enhanced Coalbed Methane (ECBM)</td>
<td>3</td>
</tr>
</tbody>
</table>

* Assumes that ECBM operators are willing to pay $8/tCO₂. It also accounts for additional emissions associated with injection and recycling of CO₂ (i.e., higher avoided costs)
Introduction

Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Storage Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Base Estimate</td>
</tr>
<tr>
<td>10% Storage</td>
<td>10% of Base Estimate</td>
</tr>
</tbody>
</table>

- **Assumptions applicable to all scenarios**
  - Plant retirement eligibility: > 30 years
  - Storage requirement: 50 years of plant emissions
  - Capital charge: power plants (7.5%), industrial plants, transport, and storage infrastructure (16.3%)
  - Capacity factor (CF): 75% for new IGCC with CCS; same CF as replaced plant for NGCC with CCS
  - Feedstock prices: $4.5/GJ NG, $1.7/GJ coal, low CO₂ prices for EOR/ECBM
  - Learning is included for capture
  - All costs in constant 2009 dollars
## Introduction Deployment

<table>
<thead>
<tr>
<th>Phase 1 – Tranche 1</th>
<th>Bonus Allowance ($/tCO2 avoided)</th>
<th>Bonus Allotment (GW capacity)*</th>
<th>Reduction Target (%)</th>
<th>Construction Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$106</td>
<td>1.64</td>
<td>N/A</td>
<td>2016</td>
</tr>
<tr>
<td>Phase 1 – Tranche 2</td>
<td>$85</td>
<td>3.28</td>
<td>N/A</td>
<td>2020</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Reverse Auction</td>
<td>11.8</td>
<td>N/A</td>
<td>2025</td>
</tr>
<tr>
<td>2030</td>
<td>N/A</td>
<td>N/A</td>
<td>30%</td>
<td>2030</td>
</tr>
<tr>
<td>2040</td>
<td>N/A</td>
<td>N/A</td>
<td>60%</td>
<td>2040</td>
</tr>
<tr>
<td>2050</td>
<td>N/A</td>
<td>N/A</td>
<td>80%</td>
<td>2050</td>
</tr>
</tbody>
</table>

**NOTE:** Bonuses apply for only first 10 years of CCS operation.

* National bonus allotments are adjusted for the southwestern region (~ 16.4% of national power capacity)
The Base Scenario
Phase 1 - Tranche 1

- # of Plants: 3 IGCC w/ CCS
- Generating Capacity: 1.64 GW
- CO₂ Avoided: 10.9 Mt CO₂ /yr
- CO₂ Storage: 2 Aquifer (67%) and 2 Oil and Gas Sites (33%)
- Avg. Pipeline Length: 80 km

Legend:
- CO₂ Pipelines
  - 13-inch
  - 16-inch
  - 24-inch
  - 30-inch
  - 36-inch
  - 42-inch
- CO₂ Sources
  - Ammonia
  - Ethanol
  - Power
  - Refinery
  - Interstates

Mean Pipe Diameter: 18 in
The Base Scenario

Phase 1 - Tranche 2 (~4% reduction)

- **# of Plants**: 5 IGCC and 1 NGCC w/ CCS
- **Generating Capacity**: 3.26 GW
- **CO₂ Avoided**: 21.1 Mt CO₂ /yr
- **CO₂ Storage**: 3 Aquifer (61%) and 2 Oil and Gas Sites (39%)
- **Avg. Pipeline Length**: 138 km

**Summary Statistics**

- Mean Pipe Diameter: 17 in

Legend:
- **CO₂ Pipelines**
  - 13-inch
  - 16-inch
  - 24-inch
  - 30-inch
  - 36-inch
  - 42-inch

**CO₂ Sources**
- Ammonia
- Ethanol
- Power
- Refinery
- Interstates

*UC Davis Sustainable Transportation Energy Pathways*

An Institute of Transportation Studies Program
The Base Scenario

Phase 2 (~15% reduction)

- **Summary Statistics**
  - # of Plants: 14 IGCC and 2 NGCC w/ CCS
  - Generating Capacity: 11.8 GW
  - CO₂ Avoided: 71.9 Mt CO₂ /yr
  - CO₂ Storage: 9 Aquifer (68%) and 5 Oil and Gas Sites (32%)
  - Avg. Pipeline Length: 112 km
The Base Scenario
2030 (~30% reduction)

Summary Statistics
- # of Plants: 21 IGCC, 2 NGCC, 1 ethanol, and 1 ammonia
- Generating Capacity: 23.6 GW
- CO₂ Avoided: 143 Mt CO₂ /yr
- CO₂ Storage: 16 Aquifer (77%), 7 Oil and Gas Sites (18%), and 1 ECBM (5%)
- Avg. Pipeline Length: 103 km

Legend
- 13-inch CO₂ Pipelines
- 16-inch CO₂ Sources: Ammonia
- 24-inch CO₂ Sources: Ethanol
- 30-inch CO₂ Sources: Power
- 36-inch CO₂ Sources: Refinery
- 42-inch CO₂ Sources: Interstates

Mean Pipe Diameter: 21 in
The Base Scenario
2040 (~57% reduction)

- **Summary Statistics**
  - # of Plants: 36 IGCC, 3 NGCC, 1 ethanol, and 1 ammonia
  - Generating Capacity: 46.5 GW
  - CO₂ Avoided: 279 Mt CO₂ /yr
  - CO₂ Storage: 29 Aquifer (86%), 7 Oil and Gas Sites (11%), and 2 ECBM (3%)
  - Avg. Pipeline Length: 119 km

Legend:
- CO₂ Pipelines
  - 13-inch
  - 16-inch
  - 24-inch
  - 30-inch
  - 36-inch
  - 42-inch
- CO₂ Sources
  - Ammonia
  - Ethanol
  - Power
  - Refinery
  - Interstates
The Base Scenario
2050 (~75% reduction)

- **Summary Statistics**
  - # of Plants: 37 IGCC, 36 NGCC, 7 ethanol, 2 ammonia, and 1 refinery
  - Generating Capacity: 90.5 GW
  - CO₂ Avoided: 363 Mt CO₂ /yr
  - CO₂ Storage: 43 Aquifer (85%), 17 Oil and Gas Sites (11%), and 2 ECBM (4%)
  - Avg. Pipeline Length: 89 km

[Map and graph showing pipeline distribution and diameters]
The Base Scenario

Small local CO₂ pipeline networks develop as a result of the availability of storage capacity throughout the region. Large interconnected regional networks are not necessary.

Phase 1 - Tranche 1

Phase 2

2050

Legend

- **CO₂ Pipelines**
  - 13-inch
  - 16-inch
  - 24-inch
  - 30-inch
  - 36-inch
  - 42-inch

- **CO₂ Sources**
  - Ammonia
  - Ethanol
  - Power
  - Refinery
  - Interstates
The Base Scenario

Transport costs decrease with time, but total average levelized cost increases as bonuses expire and sources with higher capture costs are required to meet reduction targets.
The Base Scenario

Bonus allowances allow early adopters of CCS to derive benefits even when the CO₂ price is at the clearing price, but significant adoption of CCS will continue only if the CO₂ price is above the clearing price.

NOTE: In each construction phase, all infrastructure is built in the first year.
The Base Scenario

About 300 MtCO$_2$/year can be avoided at a levelized cost below ~$50/tCO$_2$, using primarily IGCC with CCS; cost increases quickly as NGCC and industrial sites adopt CCS.
The 10% Storage Scenario

With 10% of the original capacity, a more extensive pipeline network is required in order to access additional injection sites.

Base (2050)
86 Sources/ 62 Sinks

10% Storage (2050)
85 Sources/ 81 Sinks
The 10% Storage Scenario

A map of the location of capacity constraints indicates that the main driver for the development of large interconnected regional networks is insufficient local storage capacity.
Four sub-cases were explored:

- **Organic Growth:**
  - Pipeline network is optimized in each deployment phase; additional capacity is added as needed

- **Point-to-Point:**
  - Each CO₂ source has a dedicated independent pipeline

- **Oversizing (10-yr Foresight):**
  - Tranche 1 and 2 pipelines (2016 and 2020) are oversized for flows in Phase 2 (2025) and Phase 2 pipelines are oversized for flows in 2030; no oversizing in 2030 and beyond

- **Oversizing (2050 Foresight):**
  - 2050 Foresight: All pipelines oversized for flows in 2050
Comparison of Sub-cases

In evaluating the net present cost of each sub-case, an economic argument may be made for oversizing pipelines for near-term flow projections (<10 years), but not long-term projections.
Relevance to Bioenergy

![Graph showing emissions of CO2 over time from 2000 to 2100 with different scenarios: World - GCAM - AM2S2, World - MESSAGE - AM2S2, World - REMIND - AM2S2.](generated: 2013-10-07 18:28:26)
Benefits of coupling a spatially-explicit CCS model with BeWhere

- Facilitate the estimation of supply curves for bioenergy \textit{with} CCS
- Refine estimates regarding the economic potential for bioenergy \textit{with} CCS
- Identify potential prime locations for bioenergy production \textit{with} CCS
Thank you

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Insights - Design

- The development of regional pipeline networks is driven primarily by insufficient local storage capacity.

- Oversizing pipelines for future flows increases the overall project cost.

- The optimal pipeline deployment strategy is regionally specific.
Insights - Cost

- The bonuses in the K-L bill are adequate to incentivize CCS. Beyond the bonus period (2030 and beyond), the CO₂ price must remain above the clearing price to drive further investment.

- The average levelized cost of CCS increases over time as bonuses expire and plants with higher capture costs are required.

- About 300 Mt/yr can be avoided at a cost below ~$50/t CO₂.
The 10% Storage Scenario

A map of the location of capacity constraints indicates that interconnected large regional networks develop to access new storage capacity.

Legend
- CO2 Sources
- Percent Storage Capacity Used
  - <= 90%
  - > 90%
- CO2 Pipelines
The 10% Storage Scenario

The pipeline length is generally between 30 to 50% larger ...

... which translates to a 30 to 75% increase in the transport cost and 3 to 10% increase in the total levelized cost
The Base Scenario

Oversizing pipelines in anticipation of future flows results in a larger total project cost (~$230 million); discount rate would need to be ~2% to favor oversizing in the base scenario.

In Phases 1 and 2, oversizing results in early construction of larger diameter pipelines, ...

... but also results in less pipeline since redundant lines are not needed and better economies of scale in the long term (2050).