Making Carbon Capture, Utilization and Storage a Reality: Integrating Science and Engineering into a Business Plan Framework*

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Abstract

Carbon capture, utilization, and storage (CCUS) is a key mitigation technology capable of reducing CO₂ emissions on an industrial scale without requiring a fundamental restructuring of energy systems. To have a meaningful impact, CCUS will need broad implementation that requires power utilities to develop comprehensive business plans integrating electricity production, CO₂ capture, CO₂ transport, utilization revenue, and CO₂ storage issues. Developing such business plans is a significant challenge, and CCUS has thus far had a very limited impact in mitigating CO₂ emissions (~40 million tonnes of CO₂ mitigated in 2014 versus global emissions estimated around 40 billion metric tons). In this paper, a first-of-a-kind framework termed SimCCUS is introduced that integrates key CCUS science, engineering, and economic concerns, allowing stakeholders to assess the feasibility and business impact of distinct business plans. Specifically, the framework has the novel capability to evaluate four separate business-model strategies, ranging from full vertical integration (e.g., power utility and subsidiaries are responsible for capture, transport, utilization, and storage of CO₂) to pay-at-the-gate models (utility pays a third party to handle emissions from the power plant site). SimCCUS integrates geological models of CO₂ utilization and storage in stacked reservoir systems (deep saline formations underlying utilization options for enhanced oil recovery, enhanced coal-bed methane production, and enhanced gas recovery) with engineering and economic parameters to design optimal CCUS infrastructure networks that allow stakeholders to assess which, if any, CCUS business model is most feasible. Using a case study of a representative coal-fired power plant in the Illinois Basin (USA) we illustrate how the feasibility of different business models varies with market (e.g., oil
price) and regulatory (e.g., CO₂ emissions price) conditions, as well as desired CO₂ capture and electricity-generation rates. The framework shows how, where, and when CCUS infrastructure should be constructed, including propensity for utilization options to be deployed early in the project lifecycle, followed by stacked saline formation storage that leverages existing surface infrastructure. Given the further advantage of facilitating connections between power utilities and businesses interested in CO₂ utilization, it is hoped that SimCCUS could be a key tool for jumpstarting CCUS in the near future.

Reference Cited

Making Carbon Capture, Utilization and Storage a Reality: Integrating Science and Engineering into a Business Plan Framework

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Issue: Despite significant, global R&D effort, CCUS technology is mitigating < 0.1% of global CO$_2$ emissions.

Source: Global CCS Institute, 2014
Objective: Develop new decision support tool for CCUS

**DESCRIPTION**

- coupled *economic-engineering* decision-making framework for CCS *scientists*, *stakeholders*, and *policy makers*
- understand how CCS technology—capture, transport, storage—could and should be deployed on an *industrial scale*
  - *SimCCUS*SUPCAP*: cap-and-trade environment*
  - *SimCCUS*SUPPRICE*: CO₂ tax*
  - *SimCCUS*SUPTIME*: infrastructure evolution

**OPTIMIZATION ENGINE**

- **Cost to open source capture CO₂**
- **Cost to purchase land, construct pipeline, and transport CO₂**
- **Cost to open reservoir, inject CO₂**

**PARAMETERS**

- CO₂ flow must be less than maximum pipeline capacity
- CO₂ flow must be more than minimum pipeline capacity
- CO₂ flow leaving a node must equal inflow
- CO₂ captured at a source must not exceed supply
- CO₂ stored at a sink must not exceed capacity
- Target amount of CO₂ to store or sequester
- Only one pipeline can be built between nodes

**INTERFACE**

- custom/open-source GIS, network generation, model building

**POLICY ANALYSIS**

- Spatial analysis
- Economics & engineering
SimCCUS: Scalable Infrastructure Model for CCUS

**DATA**
- Roads, waterways, rail, topography, state/federal lands, right-of-way, urban areas, ...
- CO₂ separation and compression equipment costs, financing, electricity cost, ...

**COST MODEL**
- Cost surface
- Raw network
- Candidate arcs

**ENGINEERING MODEL**
- Diameters
- Pressure drop
- Cost per length
- Capacity

**NETWORK MODEL**
- Number of wells
- Flow to reservoir

**CANDIDATE NETWORK**
- Well, drilling, leasing, reworking, operating; Electricity cost, pressurization equipment, financing, ...
- Permeability, thickness, depth, temperature, viscosity, pressure, radius, pore space; Well diameter, friction factor; ...

**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
- Which reservoirs should inject/store CO₂

**CO₂ FLOWS**
- CO₂ amount to be captured at each source
- How much CO₂ should be stored in each reservoir
- CO₂ pipeline capacities

**GENERAL**
- Amount of CO₂ cost-effectively sequestered
- Scale of CCS infrastructure
- Policy implications
- Tradeoff between capture, transport, and storage
SimCCUS: Scalable Infrastructure Model for CCS

Impact on electricity generation costs

Boiler-level generation and emissions

Full cost of bituminous (A) and sub-bituminous (B) coal

Without CO₂ capture

With CO₂ capture

Electricity costs (1st y-axis)

CO₂ (2nd y-axis)

Bituminous

Fixed

Fixed O&M

Variable O&M

Sub-bituminous

Fixed

Fixed O&M

Variable O&M

Emitted

Captured

Total

Electricity cost ($/MWh)

CO₂ mass (MtCO₂/yr)

a. New build

b. Existing

c. New build

d. Retrofit

24 6 8 10 12 14 16 18 20 22 24

Hour

Normalized Output (MWh)

Boiler-level generation and emissions

Days

Boiler 5

Boiler 4

Boiler 3

Boiler 2

Boiler 1

CO₂ emissions (tCO₂/d)

Annual CO₂ equivalent (MtCO₂/yr)
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SimCCS

Framework

Case study

Storage

Results

Future work

Conclusions

Parameters

SimCCUS: Scalable Infrastructure Model for CCUS

Novel weighted-cost surface

Pipeline economies of scale

Discrete path analysis

(a) Raster paths
(b) Identify nodes
(c) Network with duplicates
(d) Raw candidate network

Multi-fidelity network refinement
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Parameters

Region Scale
(10km-1,000km)

Site Scale
(100m-10km)

Reservoir Scale
(10cm-100m)

Pore Scale
(10nm-10cm)

Nano Scale
(A-10nm)

CO₂ Pipeline

Power Plant

Injection Site

abandoned oil/gas well

injection well

abandoned oil/gas well

Brine Reservoir

CO₂ Plume

Core Flooding and Reactive Transport Modeling

Beach Scale Experiments and Lattice Boltzmann Modeling

Mineral Fluid Experiments and Theoretical Geochemistry

Geo chemistry

Mineral Fluid Experiments and Theoretical Geochemistry

Dissolution & precipitation

Mineral Fluid Experiments and Theoretical Geochemistry

Produced water (m³/ton CO₂)

Temperature (°C)

Reservoir capacity (MtCO₂)

Injection/extraction cost ($/ton CO₂)

CO₂ Saturation

Analytical solution

24 days

Radius (m)

Height (m)

20 30 40 50 60 70 80 90 100

2 5 6 9 10 17 18 20 26

1 7 10 13 17 19

12 13 14 17 20 26

200 400 600 800 1000
Case study: Gibson Generating Station

- Emissions: Up to 15 MtCO$_2$/yr
- Capture cost: $65/tCO$_2$
- 15 coupled storage-utilization sites
- Stacked storage: saline & utilization
- First order CO$_2$ utilization values
  - EOR: $40/tCO$_2$
  - ECBM: $5/tCO$_2$
  - Shale gas: $10/tCO$_2$

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<th>Location</th>
<th>utmX</th>
<th>utmY</th>
<th>SF-MTSMN</th>
<th>SF-KNOX</th>
<th>SF-STPTR</th>
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<th>ECBM/UC</th>
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</tbody>
</table>

Color codes: relative resource level--- high resource, med resource, low resource
Overview: CO₂ source and reservoirs

**Sinks**
- 15 sites
- 6 potential reservoirs at each site
- 73 total reservoirs

**Cost surface**
- Based on geographical features (e.g., slope, ROWs, land ownership, transmission lines, roads, rivers, etc.) → potential pipeline routes
Overview: candidate pipeline network

**Sinks**
- 15 sites
- 6 potential reservoirs at each site
- 73 total reservoirs

**Cost surface**
- Based on geographical features (e.g., slope, ROWs, land ownership, transmission lines, roads, rivers, etc.)
- potential pipeline routes
Stacked saline formations

- Knox, Mt. Simon, and St. Peter
- Storage costs driven by: injectivity, plume radius, depth, water production & treatment, storage capacity, distribution pipelines...
**Oil and Gas Reservoirs**

- Cumulative production of >4.3B bbl
- 1600+ fields with production data and extensive characterization
- OOIP calculated for each field: $OOIP = Ah\phi(1-S_w)/B_o$
- OOIP validated with exponential decline curve analysis (IL) and cumulative production data
- EOR and storage resource calculated from miscibility class and prior studies for RF and net utilization parameters
Coal seams

- Extensive mapping of all Pennsylvanian seams
- COMET model simulations of CO₂ injection and methane production for 80-acre 5-spot pattern with parameter distributions at 3 depth divisions
- Gas recovery and storage efficiency factors from COMET modeling applied in ArcGIS for volumetric calculations of ECBM and CO₂ storage estimates
• Organic-rich New Albany Shale formation
• Extensive mapping throughout the basin
• Density logs from 131 wells used to estimate TOC
OGIP $f(P, \text{TOC})$ calculated from normal pressure assumption (hydrostatic) and Langmuir adsorption isotherms from measured data (high and low TOC samples) interpolated to estimate NAS average (TOC = 5.49%).
Scenario 1: CO$_2$ cap (0.5 to 15 MtCO$_2$/yr)
• Reservoirs deploy according to CO$_2$ “credit”
• EOR/ECBM offset storage costs, even at 15 MtCO$_2$/yr
• Economies of scale drives down transport costs
• Marginal costs drive CCUS decisions
- Reservoirs deploy according to CO₂ “credit”
- EOR/ECBM offset storage costs, even at 15 MtCO₂/yr
- Economies of scale drives down transport costs
- Marginal costs drive CCUS decisions
• Estimate infrastructure in response to CO$_2$ tax
• 10% emissions cannot be captured and is subject to CO$_2$ tax
• CO$_2$ stored using EOR until ~$60/tCO$
Scenario 2 Analysis: CO₂ tax
Scenario 3 Analysis: Dynamic CCUS Infrastructure

- Deploy infrastructure during multiple project periods
- Potentially overbuild infrastructure in early stages
- Adapt to future conditions
- Efficient & robust infrastructure design

Click images to activate animation

<table>
<thead>
<tr>
<th>Project period</th>
<th>CO$_2$ target</th>
<th>Cumulative CO$_2$</th>
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<td>1 MtCO$_2$/yr</td>
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<td>4-6 yrs</td>
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<td>13-15 yrs</td>
<td>5 MtCO$_2$/yr</td>
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<tr>
<td>16-30 yrs</td>
<td>10 MtCO$_2$/yr</td>
<td>117 MtCO$_2$</td>
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</table>
Making CCUS a reality will require rigorous integration of extensive R&D results into a business plan framework

- Robust analysis needs for capture and storage (costs, capacities, injection rates), emission costs & prices, policies, energy prices...
- New certainty in the USA on power plant emissions.
- Identify hidden opportunities for CCUS implementation via CO₂ utilization.

**Significant innovations with SimCCUS**

- Multiple CO₂ utilization options and stacked reservoirs.
- Integrated storage and utilization planning.
- “Vertical integration” → “pay at the gate” business models.