Carbon Capture and Storage (CCS)

- **(1) Capture**
  - capture CO₂ at the source (e.g. power plants, cement works, ammonia, gas processing, refineries)
  - compress CO₂ (i.e. to liquid)

- **(2) Transport**
  - pipelines
  - source may be located above geologic reservoir

- **(3) Store**
  - inject CO₂ into geologic sink/reservoir (e.g. abandoned oil field, saline aquifer)
  - *sequester* (USA) or *store* (rest of the world) for 1000+ years
CO₂ Capture

Amine Process for CO₂ Capture


PROBLEM
LP MODELING
RESULTS
DISCUSSION
CO₂ Storage

CCS

What?

Why?

How?

Where?

Costs

Scale

PROBLEM

LP MODELING

RESULTS

DISCUSSION

Source – Carbon Mitigation Initiative (2007)
Enhanced Oil Recovery

- Weyburn (EnCana Corp.)
  - sequester 30 million tons of CO₂ over project length
  - enhanced oil recovery (EOR)
Environmental Mitigation

- **Sleipner West (StatOil)**
  - annually inject 1 million tonnes of liquid CO$_2$ into saline aquifer (sandstone) 1km below surface
  - 600 billion tonne capacity
  - CO$_2$ tax ($100k$ per day)

Source – StatOil ASA (2007)
Current/Future CCS Projects

Monash (Australia, Fuel)
ZeroGen (Australia, Power)
Gorgon (Australia, Gas Proc)
SaskPower (Canada, Power)
Greengen (China, Power)
nZEC (China, Power)
Vattenfall (Germany, Power)
RWE (Germany, Power)
Draugen (Norway, Power)
Mongstad (Norway, Power)
Snovit (Norway, Gas Proc)
BP Peterhead (UK, Power)
E.On (UK, Power)
RWE npower (UK, Power-r)
Progressive (UK, Power)
Powerfuel (UK, Power)
FutureGen (USA, Power)
BP Carson (USA, Power)

FutureGen
- zero-emissions fossil fuel plant
- $1 billion project
- prototype plant
- operational 2012

Source – DOE (2007)
Capture and Storage Costs

- **Capture**
  - reduce power plant efficiency from 50% to ~35%
  - $40-50 per ton of CO$_2$
  - ~80% of CCS costs

- **Storage**
  - injection costs ~$5 per ton of CO$_2$

- **Transportation**
  - pipeline costs $1-3 per ton of CO$_2$

- **Current state**
  - emission tax/credit of ~$50/ton CO$_2$ ($110$/tonne carbon) would make CCS competitive
  - all major components for CCS are commercially available
  - not economically feasible
Infrastructure Scale

Problem Statement

- Efficiently decide:
  - where to capture CO₂
  - which sinks to inject CO₂
  - pipeline routes and capacities
  - allocate CO₂ between sources and sinks

- Why?
  - private enterprise will match cheapest sources/sinks at the expense of long term planning
Pipeline Routing Costs

- Create pipeline cost surface (1km resolution)
  - slope, urban areas, wetland, parks (national/state), crossings (railroad/highway)
- VB demonstration

COST SURFACE

- Highway 3
- Railroad 3
- State Parks 15
- National Parks 30
- Wetland 15
- Urban 15
- Slope 0.1, 0.4, 0.8
- Base 1

(base cost for natural gas pipelines)
Cost Grid to Network Conversion
Linear Programming (LP) Approach

- First phase of modeling
  - capture variables explaining major variability

- Simultaneously optimizing for five *dependant* decisions
  - *at which sources to capture CO$_2$*
  - *which geologic sinks to open*
  - *pipeline network route*
  - *pipeline diameter*
  - *allocate CO$_2$ between sources and sinks*

- 25 year project period
Linear Programming Variables

- $x_{ij}$: units of CO₂ transported from node $i$ to $j$
- $A_i$: amount of CO₂ captured at node $i$
- $y_{ijd}$: if pipeline constructed from $i$ to $j$ with diameter $d$
- $s_i$: if source at node $i$ is opened
- $r_j$: if reservoir at node $j$ is opened
- $F^s, F^p, F^r$: fixed cost for opening a source, pipeline, reservoir
- $V^s, V^p, V^r$: variable cost for capturing, transporting, storing CO₂
- $Q^s, Q^p, Q^r$: CO₂ capacity of source, pipeline, reservoir
- $C_j$: credit received for CO₂ stored at reservoir $j$
- $T$: target of amount of CO₂ to be stored
- $N_i, N_j$: nodes adjacent to nodes $i, j$
- $R$: set of reservoir nodes
- $S$: set of source nodes
LP Model

\[ \text{MINIMIZE} \]

\[ \sum_{i \in S} \sum_{j \in N} c_{ij} x_{ij} + \sum_{i} \sum_{j \in N} d_{ij} y_{ijd} + \sum_{j \in N} V_j^x x_{ij} \]

\[ \begin{align*}
(1) & \quad x_{ij} - \sum_{d} Q_{ijd}^p y_{ijd} \leq 0 & \forall i, j \in N_i \\
(2) & \quad \sum_{j \in N_i} x_{ij} - \sum_{j \in N_{i \in R}} x_{ji} - A_i = 0 & \forall i \\
(3) & \quad A_i - Q_i^r s_i \leq 0 & \forall i \in S \\
(4) & \quad \sum_{i \in N_j} x_{ij} - Q_j^r r_j \leq 0 & \forall j \in R \\
(5) & \quad \sum_{i \in S} A_i = T \\
(6) & \quad y_{ijd} \leq 1 & \forall i, j \in N_i, d
\end{align*} \]

- **Pipeline either built or not built**
- **CO₂ flow must be positive**
- **Open source fully or not at all**
- **Open reservoir fully or not at all**

CO₂ flow must be less than pipeline diameter

CO₂ leaving a node must equal inflow

CO₂ leaving a source not to exceed supply

CO₂ entering a sink not to exceed capacity

Target amount of CO₂ to sequester

One pipeline between nodes (optional)
Sequester all CO$_2$ (25 years)
Sequester all CO₂ (25 years)
Sequester all CO$_2$ (25 years)
**Sequester CO₂ Target Amount**

![Graph showing the relationship between CO₂ Sequestered (m/t) and Total Infrastructure Cost (m$) with Solution Time (secs).]

- **CCS**
- **PROBLEM**
- **LP MODELING**
- **RESULTS**
  - Graphics
  - Graphs
  - Demo
- **DISCUSSION**

Operated by the Los Alamos National Security, LLC for the DOE/NNSA
Sequester CO$_2$ Target Amount
Sequester CO₂ Target Amount
Sequester CO$_2$ Target Amount

![Graph showing CO$_2$ sequestered vs infrastructure cost. CO$_2$ Sequestered: 30 mt.]

Operated by the Los Alamos National Security, LLC for the DOE/NNSA
Sequester CO$_2$ Target Amount

CO$_2$ Sequestered:

90

CO$_2$ Sequestered (mt)

Infrastructure Cost (m$)
Sequester CO₂ Target Amount

CO₂ Sequestered: 330 mt

Infrastructuure Cost (m$)

CO₂ Sequestered (mt)
Sequester CO$_2$ Target Amount

![Graph showing CO$_2$ sequestered vs infrastructure cost.]

- CO$_2$ Sequestered: 340
- INFRASTRUCTURE COST (m$)
Sequester CO$_2$ Target Amount

![Graph showing CO$_2$ sequestered vs infrastructure cost](image)

**CO$_2$ Sequestered:** 640 mt

Operated by the Los Alamos National Security, LLC for the DOE/NNSA
Next Steps in Modeling

- **Improvements**
  - improved data, time-steps, uncertainty, pumping stations, pressure drops

- **Future developments**

- **Scale**
Conclusions

- CCS will play a part in moving towards a carbon-neutral society
- Capture and storage costs are mostly fixed
  - efficient allocation
  - robust network
- Coal/CO₂/electricity transportation
  - coal transportation (~$9) vs. coal waste i.e. CO₂ ($1.8-5)
- Models will provide system overview and drive policy
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