Optimization for Carbon Capture and Storage

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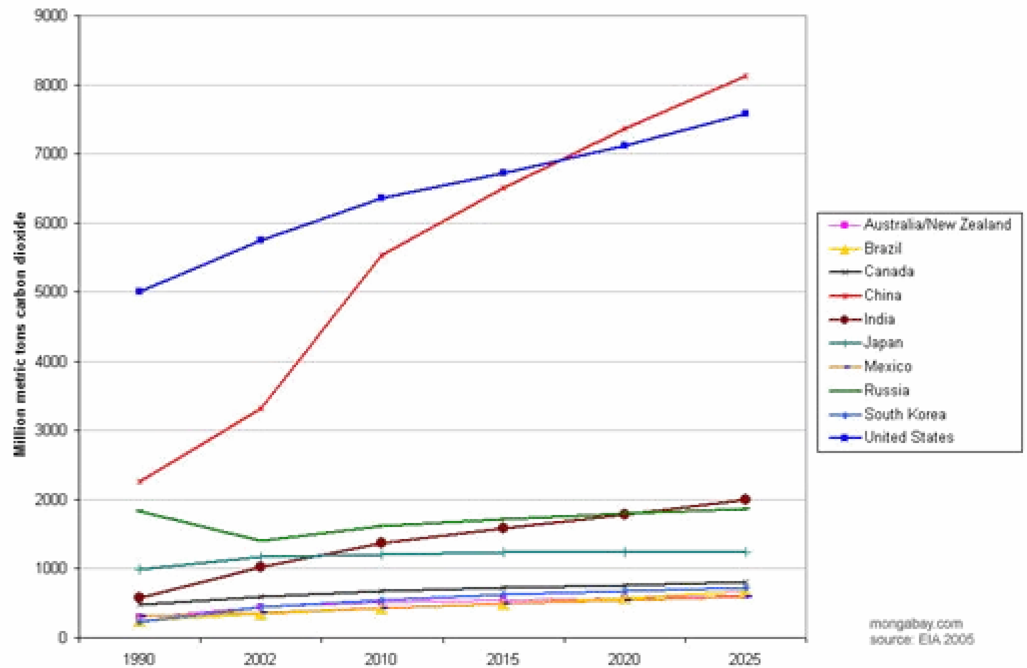
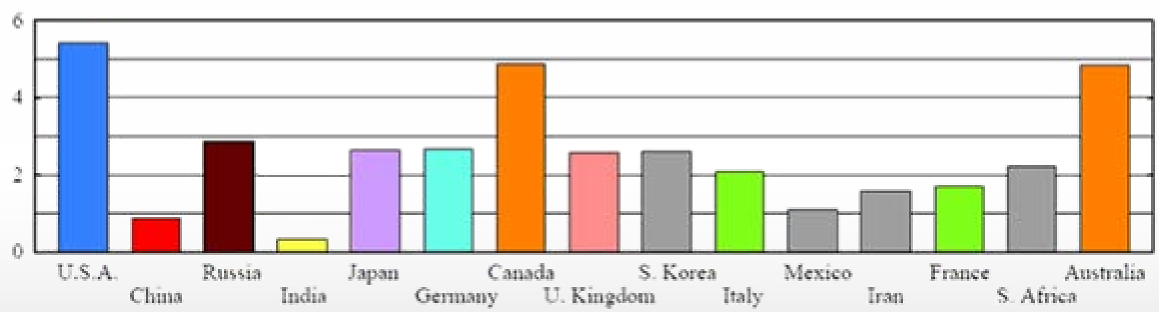
Carbon Capture and Storage (CCS)

- (1) Capture
  - capture CO_2 at the source (e.g. power plants, cement works, ammonia, gas processing, refineries)
  - compress CO_2 (i.e. to liquid)
- (2) Transport
  - pipelines
  - source may be located above geologic reservoir
- (3) Store
  - inject CO_2 into geologic sink/reservoir (e.g. abandoned oil field, saline aquifer)
  - *sequester* (USA) or *store* (rest of the world) for 1000+ years

CO_2 Emissions

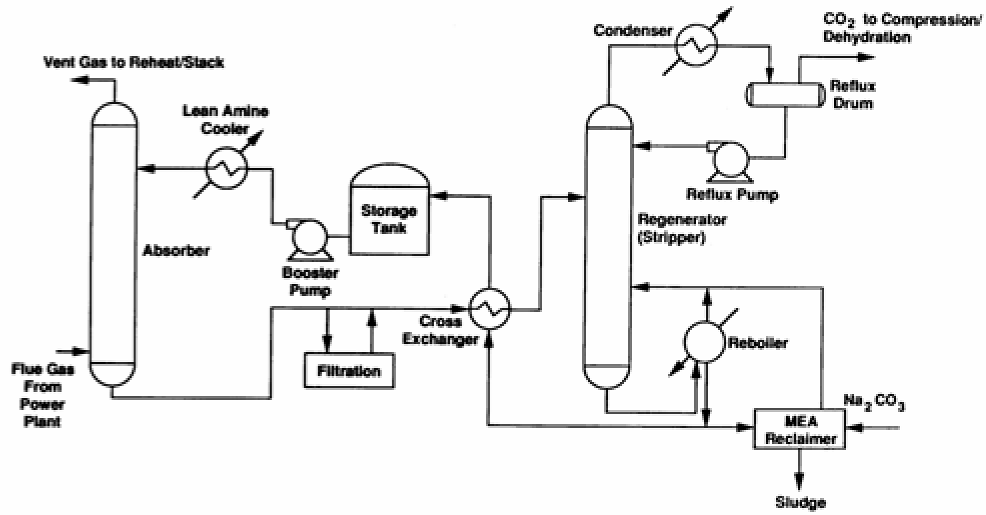




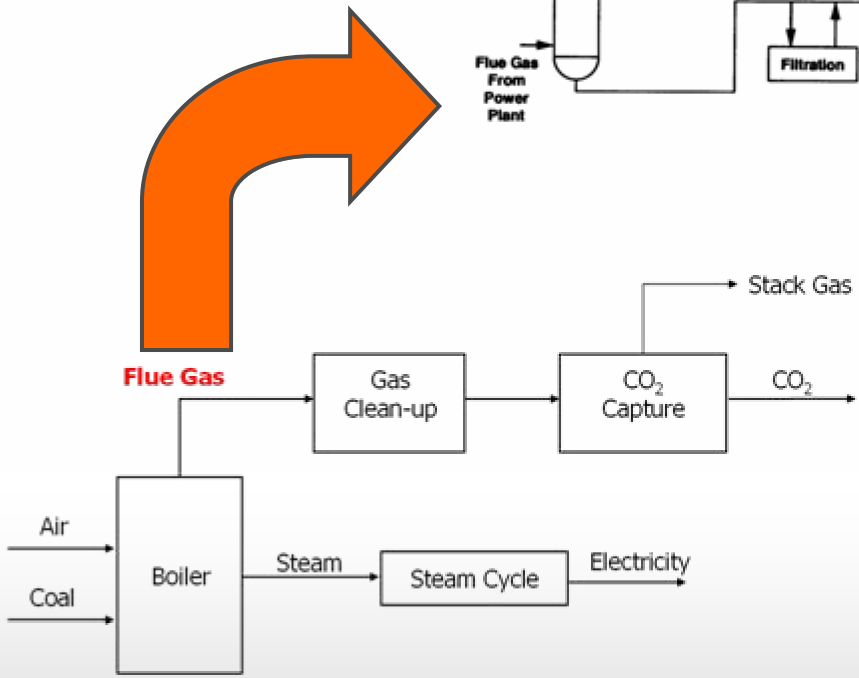
Per Capita Fossil Fuel CO_2 Emissions in Order of Total Emissions

Source – Hansen (2007)

CO_2 Capture

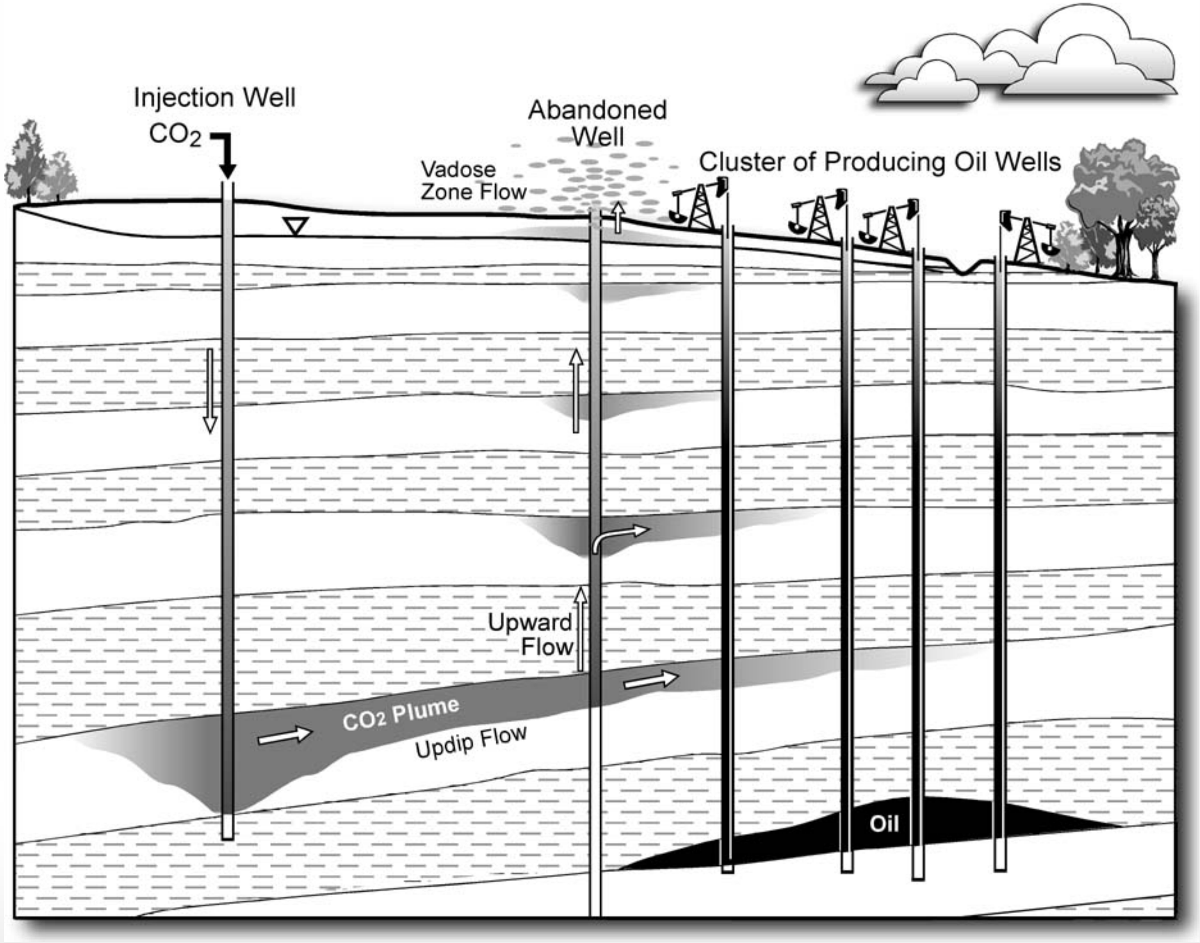


Amine Process for CO_2 Capture



Pulverized Coal Power Plant

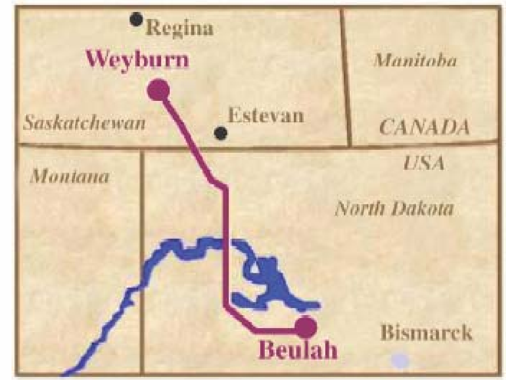
CO_2 Storage



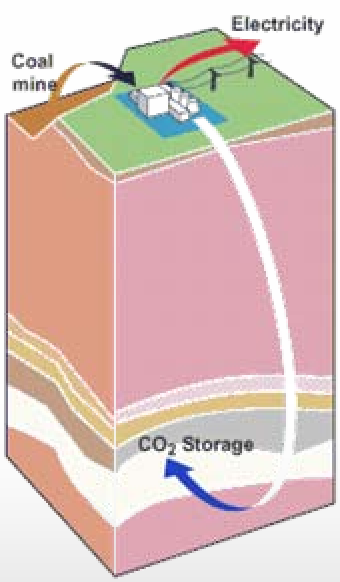
Source –Carbon Mitigation Initiative (2007)

Enhanced Oil Recovery

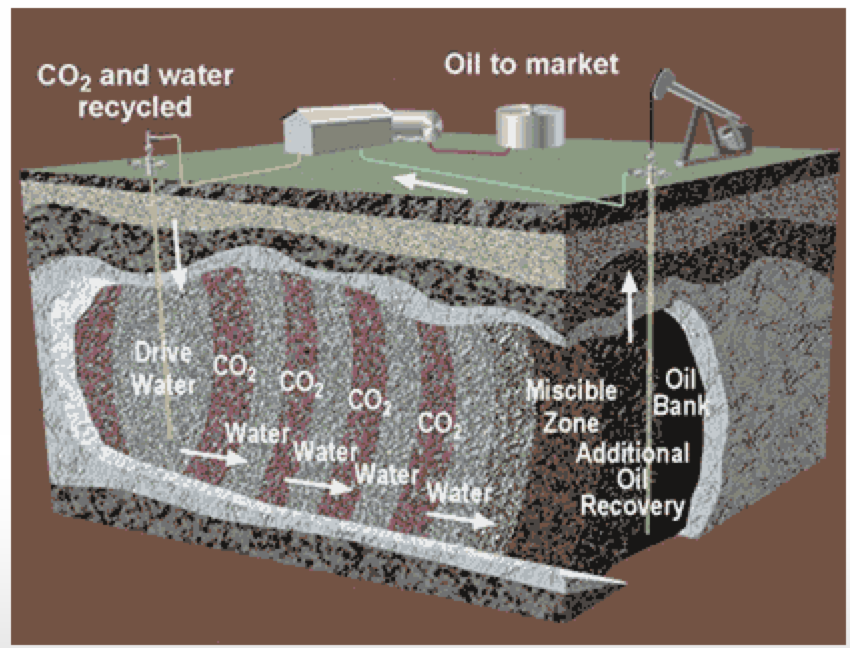
- Weyburn (EnCana Corp.)
  - sequester 30 million tons of CO_2 over project length
  - enhanced oil recovery (EOR)



Source – NRCAN (2007)



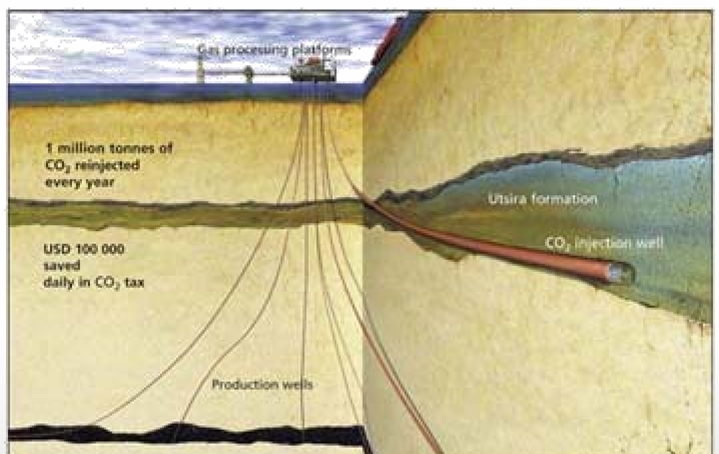
Source – CO2Store



Source – EnCana (2007)

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

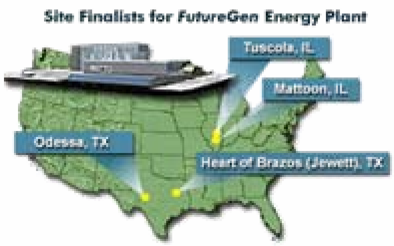
CCS

What?
Why?
How?
Where?
Costs
Scale

PROBLEM
LP MODELING
RESULTS
DISCUSSION

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

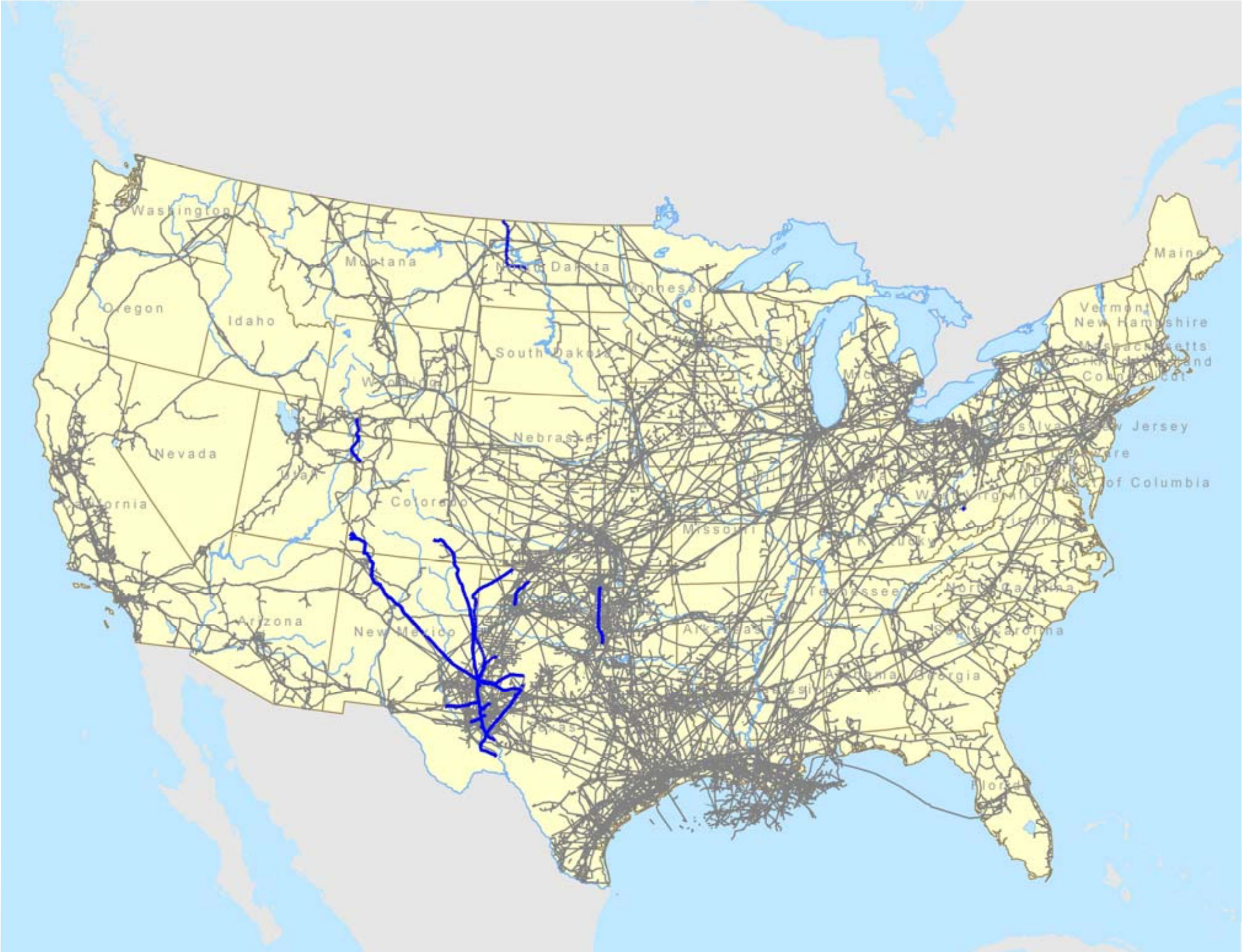


Source –DOE (2007)

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



S. Pacala and R. Socolow (2004) "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies", *Science 305*, 968-972

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PROBLEM

Definition

Data

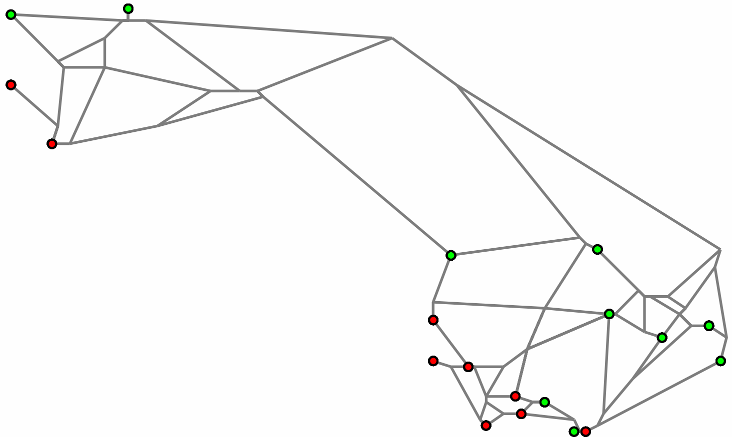
LP MODELING

RESULTS

DISCUSSION

Problem Statement

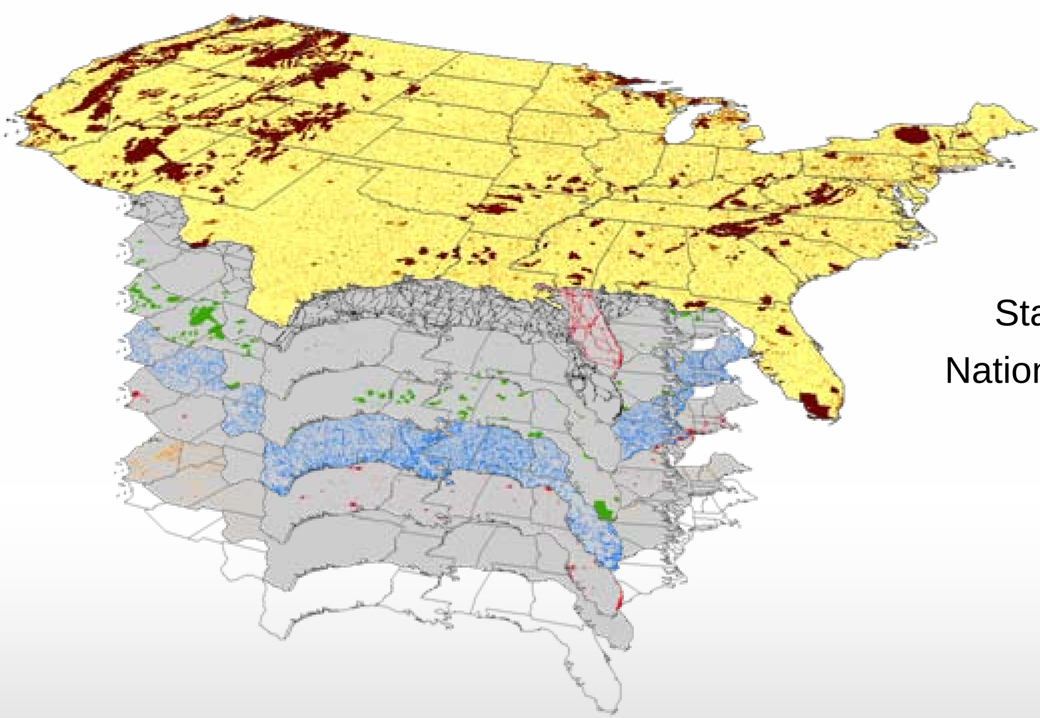
- Efficiently decide:
  - where to capture CO_2
  - which sinks to inject CO_2
  - pipeline routes and capacities
  - allocate CO_2 between sources and sinks



- 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

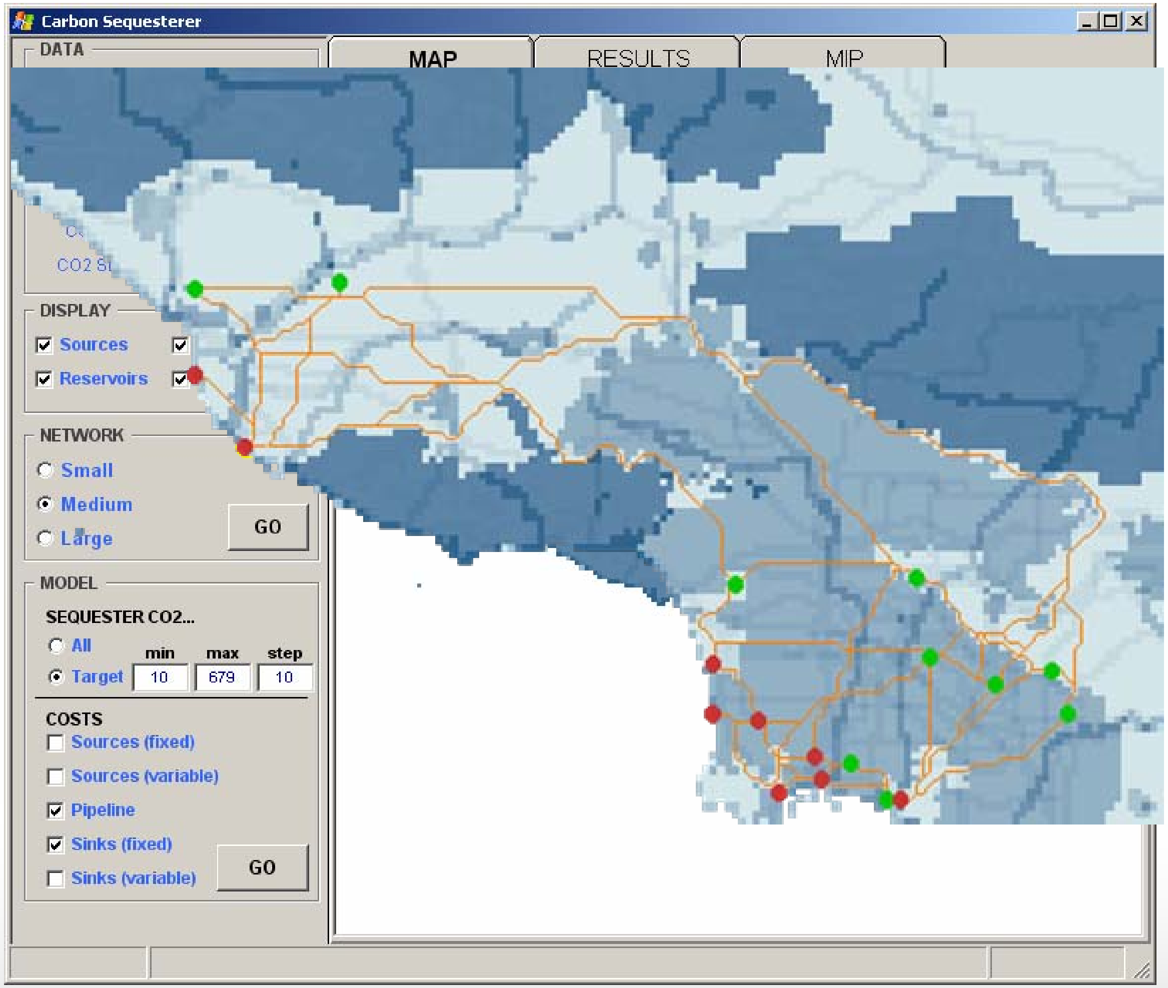


COST SURFACE

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

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PROBLEM

LP MODELING

Overview

Variables

Model

RESULTS

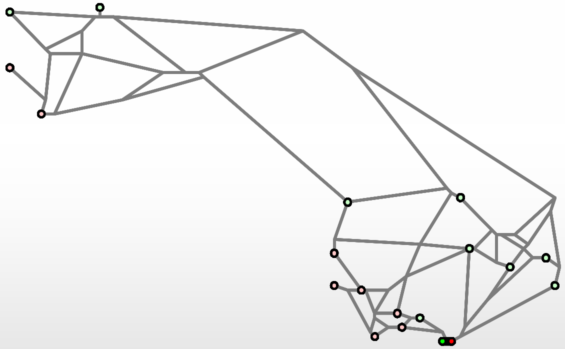
DISCUSSION

Linear Programming Variables

x_{ij} units of CO_2 transported from node *i* to *j*
A_i amount of CO_2 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 CO_2
Q^s, Q^p, Q^r CO_2 capacity of source, pipeline, reservoir
C_j credit received for CO_2 stored at reservoir *j*
T target of amount of CO_2 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

MINIMIZE

$$\sum_{i\in S} F_i^s s_i + \sum_{i\in S}\sum_{j\in N_i} V_{ij}^s x_{ij} + \sum_i \sum_{j\in N_i}\sum_d F_{ijd}^p y_{ijd} + \sum_i\sum_{j\in N_i} V_{ij}^p x_{ij} + \sum_{j\in R} F_j^r r_j + \sum_{j\in R}\sum_{i\in N_j} V_{ij}^r x_{ij}$$

Cost to open or site a source + Cost to construct and maintain pipelines + Cost to open reservoir, inject CO_2

(1) $x_{ij} - \sum_d Q_{ijd}^p y_{ijd} \le 0 \quad \forall i, j \in N_i$ — CO_2 flow must be less than pipeline diameter

(2) $\sum_{j\in N_i} x_{ij} - \sum_{j\in N_{i\notin R}} x_{ji} - A_i = 0 \quad \forall i$ — CO_2 leaving a node must equal inflow

(3) $A_i - Q_i^r s_i \le 0 \quad \forall i \in S$ — CO_2 leaving a source not to exceed supply

(4) $\sum_{i\in N_j} x_{ij} - Q_j^r r_j \le 0 \quad \forall j \in R$ — CO_2 entering a sink not to exceed capacity

(5) $\sum_{i\in S} A_i = T$ — Target amount of CO_2 to sequester

(6) $y_{ijd} \le 1 \quad \forall i, j \in N_i, d$ — One pipeline between nodes (optional)

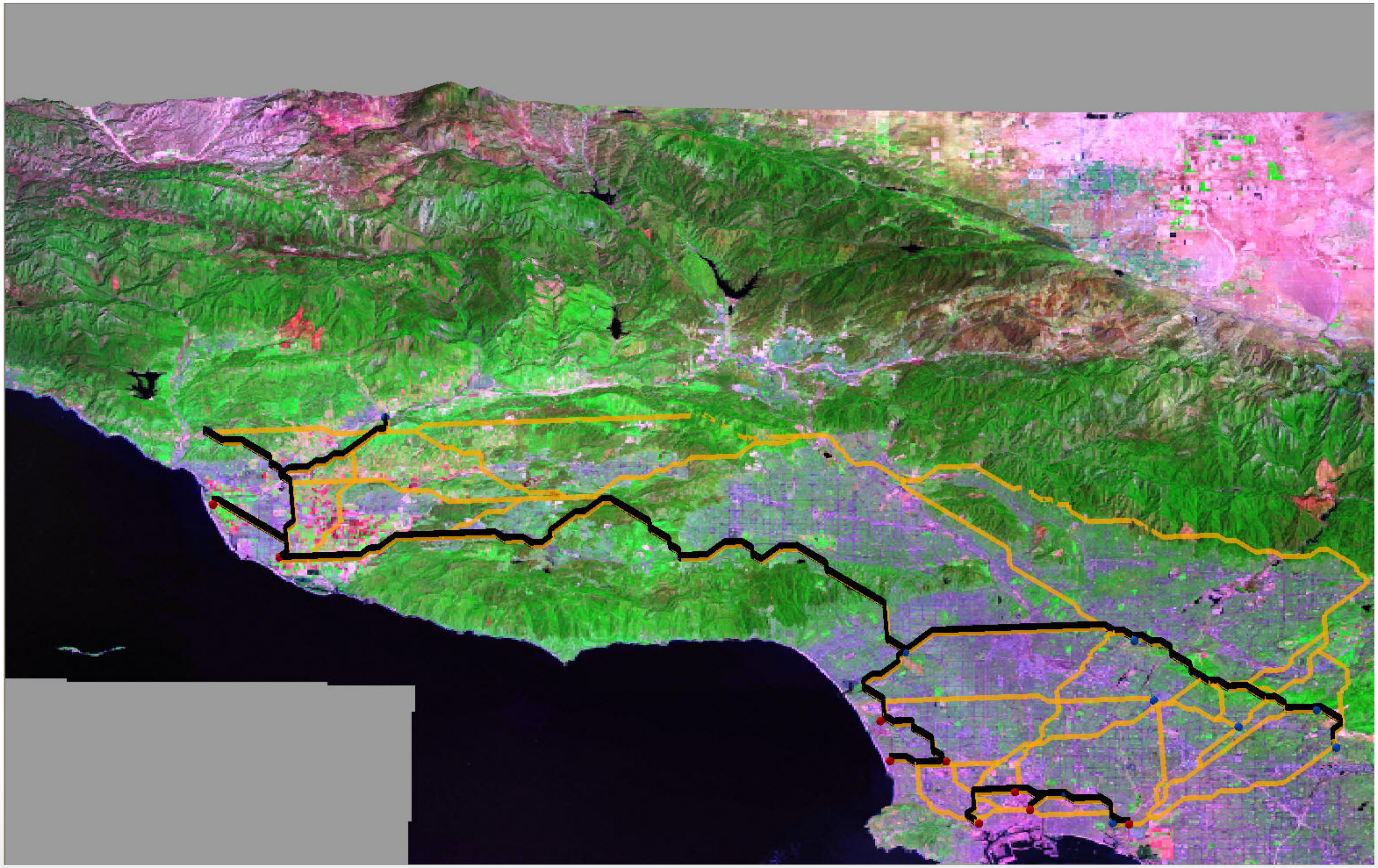
Pipeline either built or not built

CO_2 flow must be positive

Open source fully or not at all

Open reservoir fully or not at all

Sequester all CO_2 (25 years)



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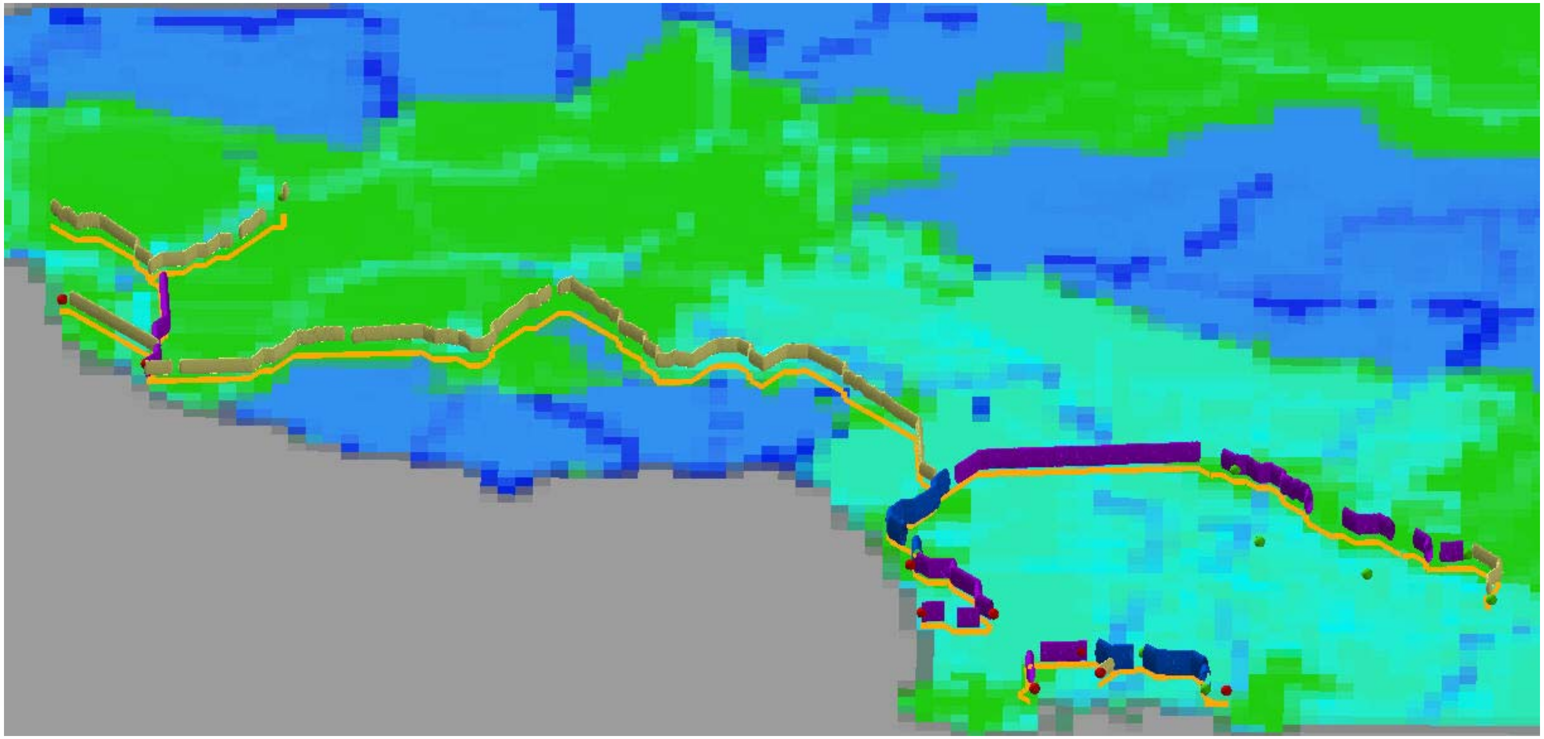

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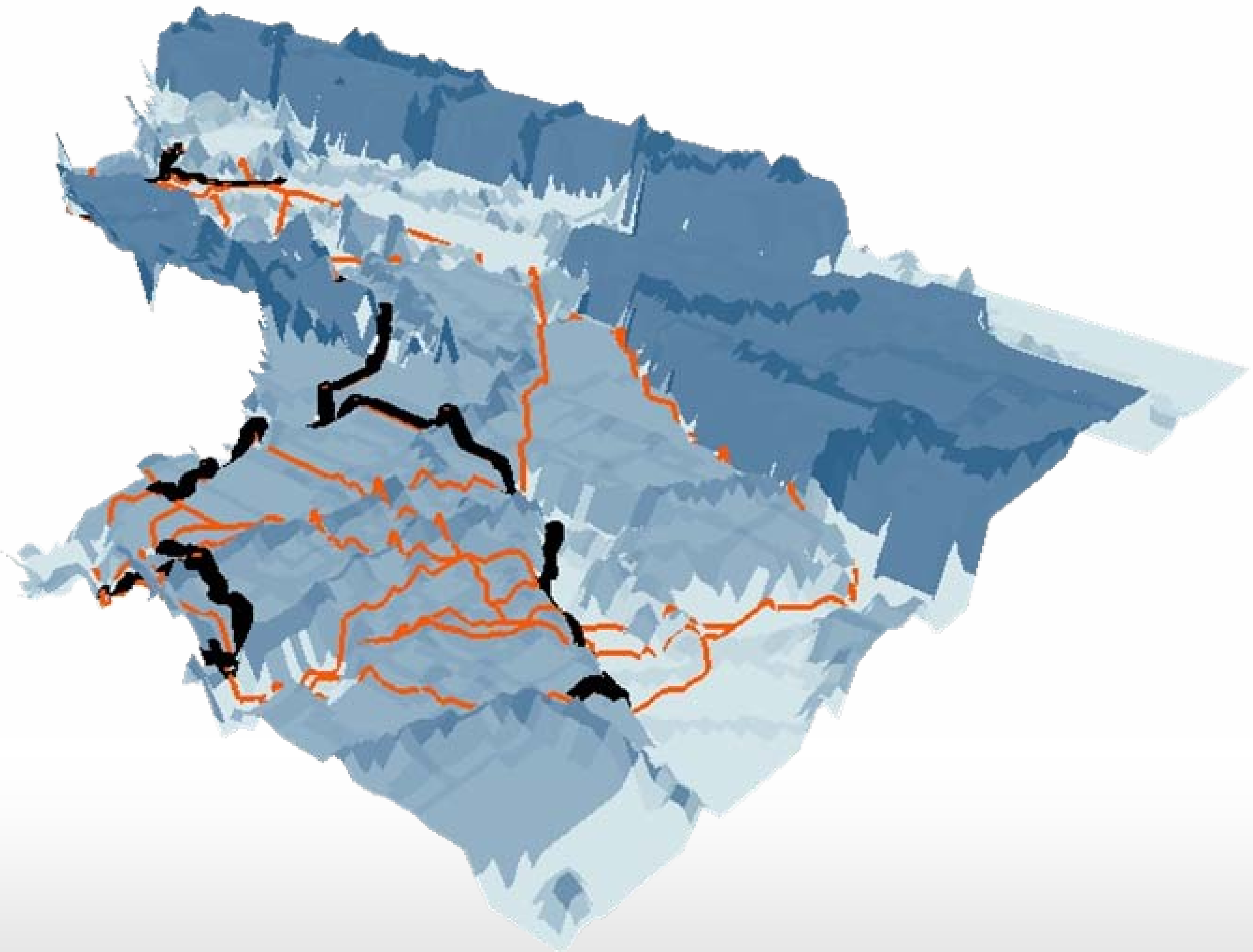
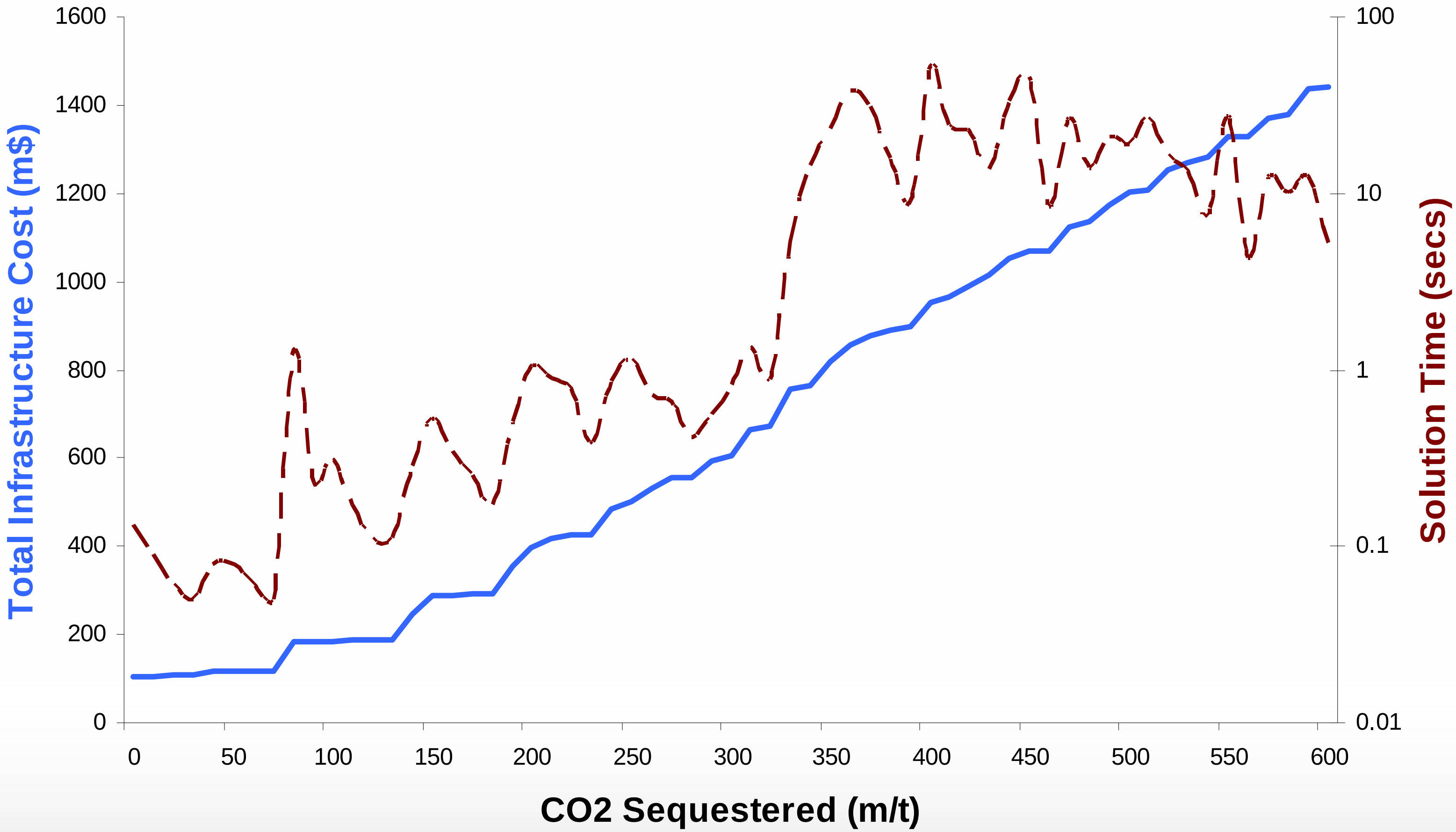


Sequester CO_2 Target Amount



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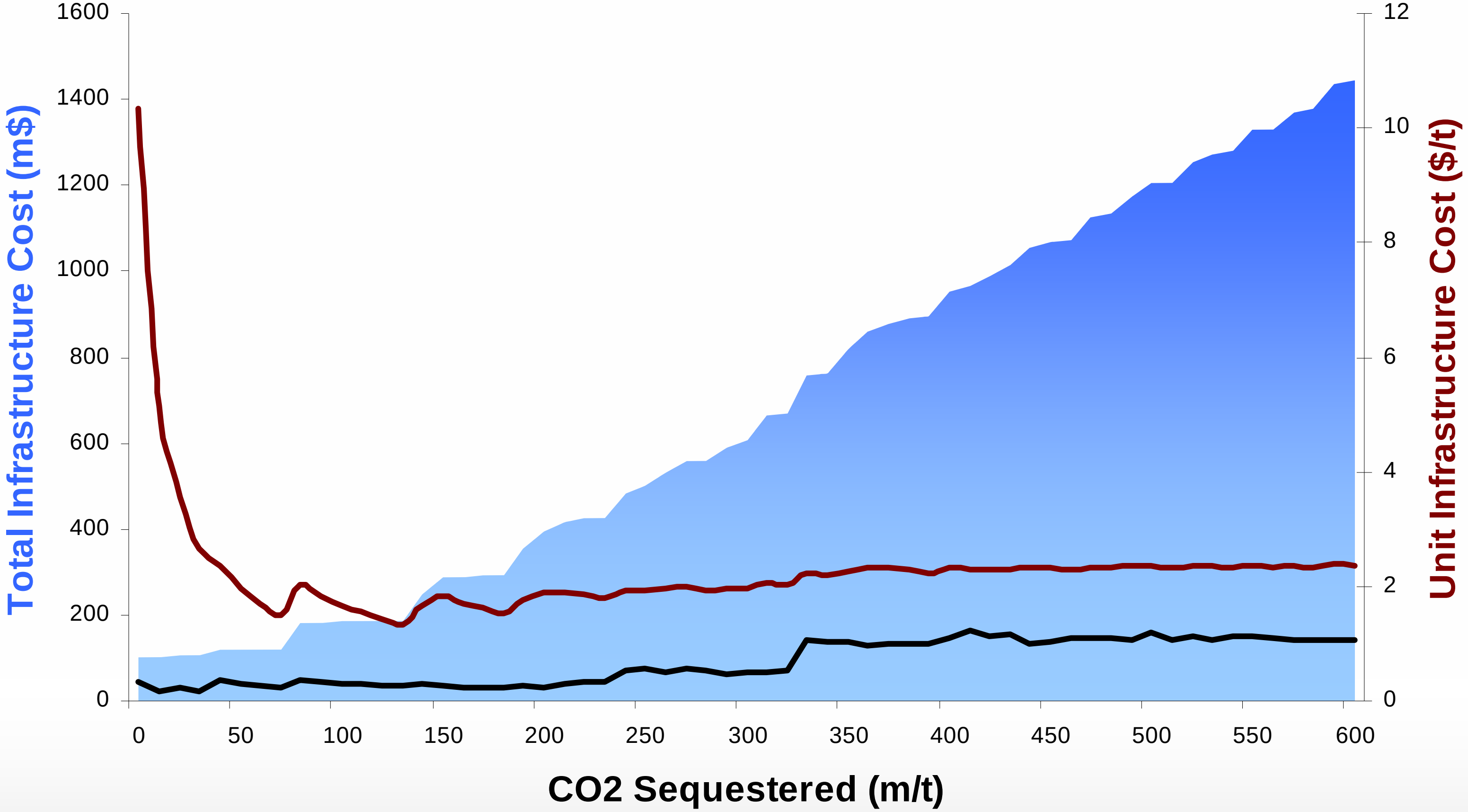

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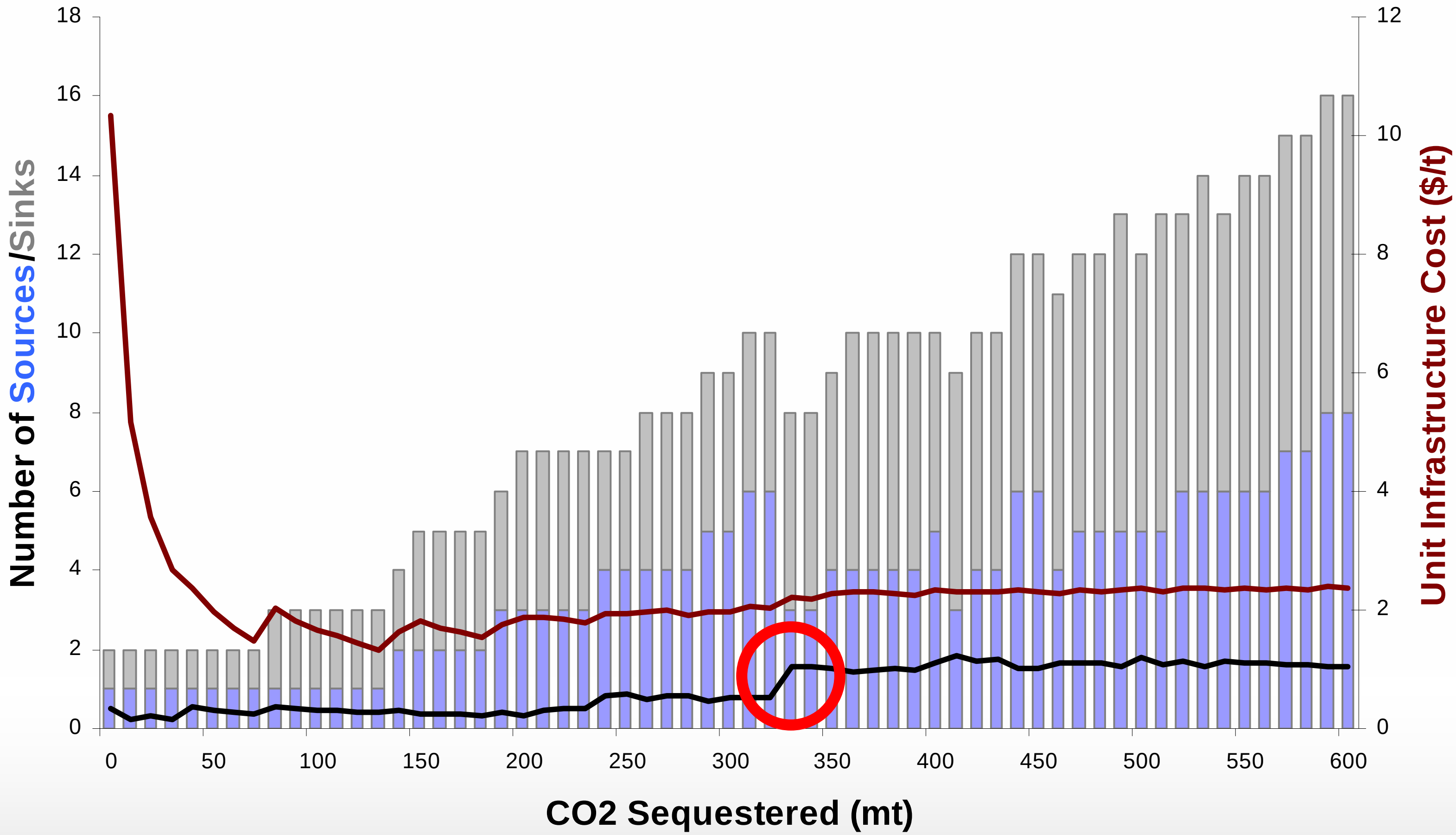

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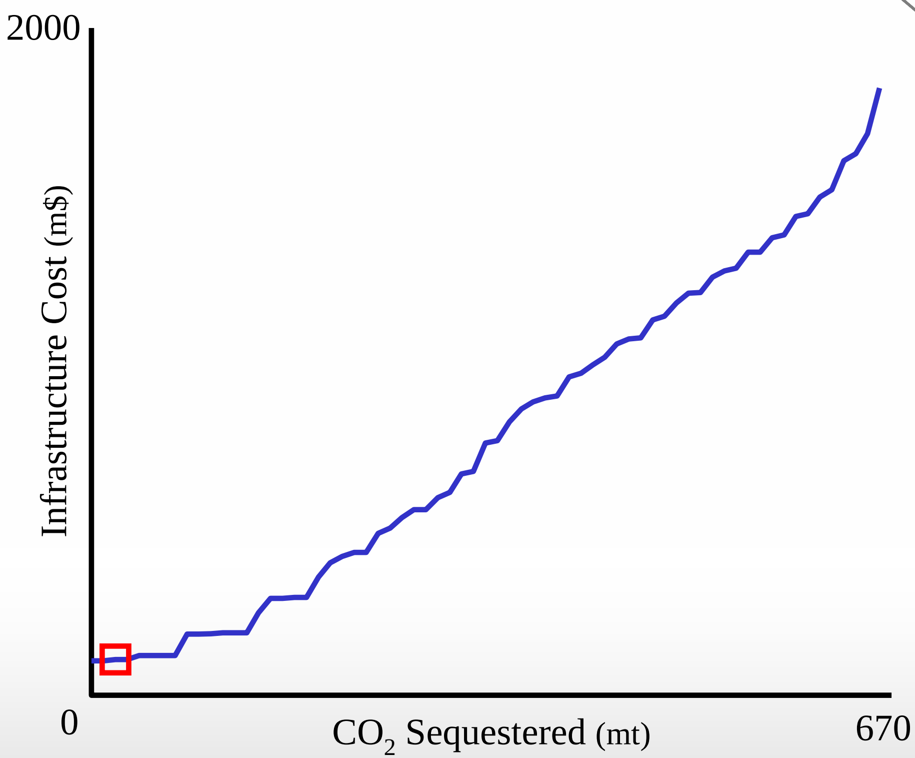
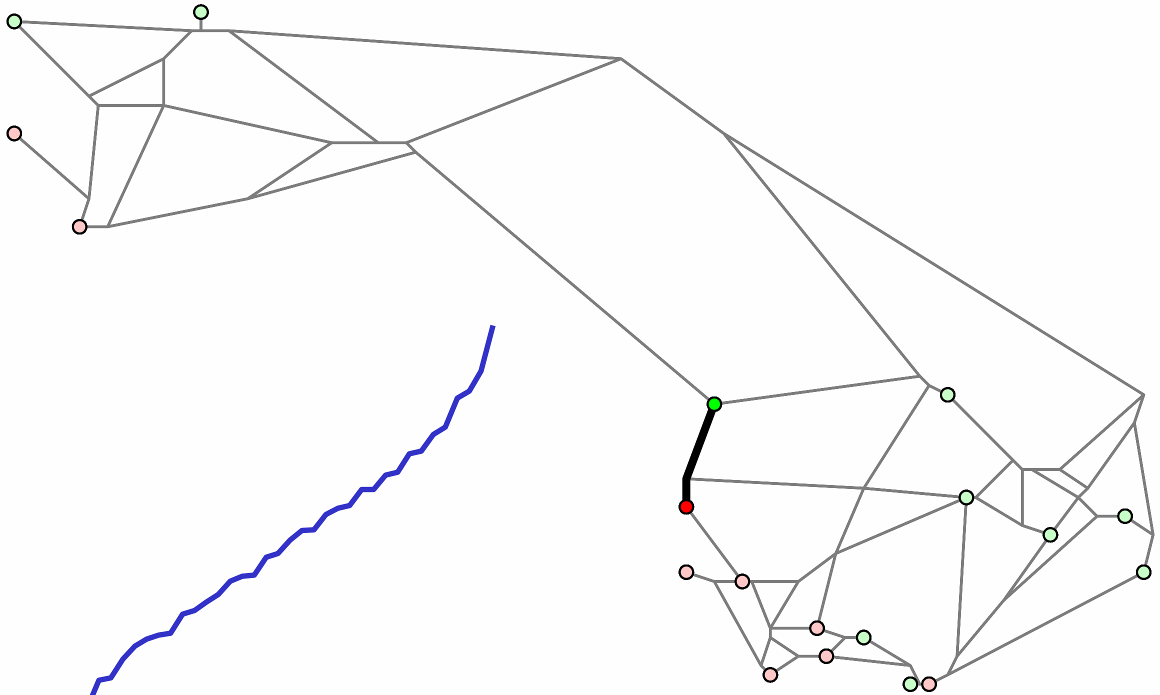
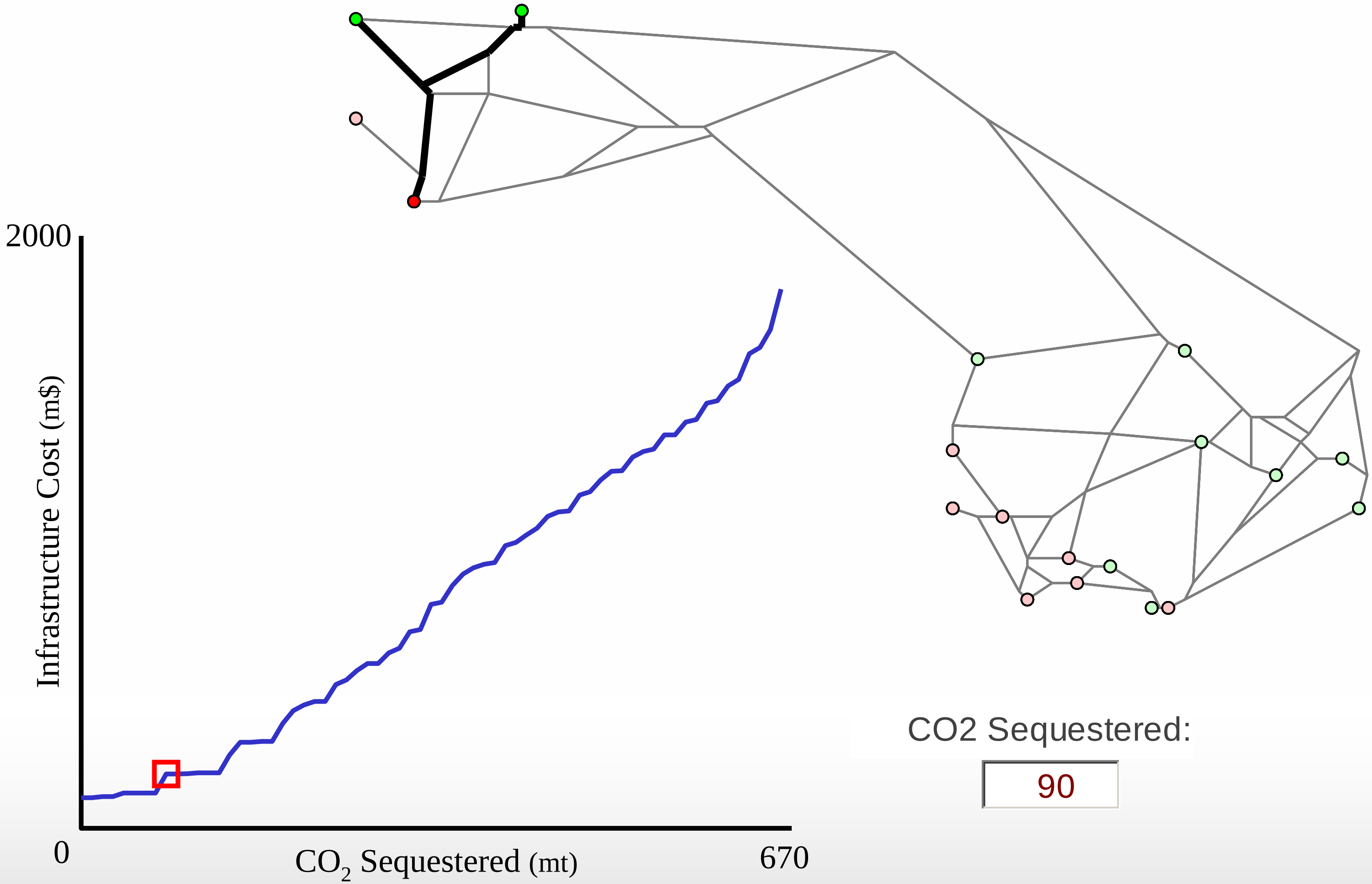




CO2 Sequestered:

30

Sequester CO_2 Target Amount



CO2 Sequestered:

90

CCS
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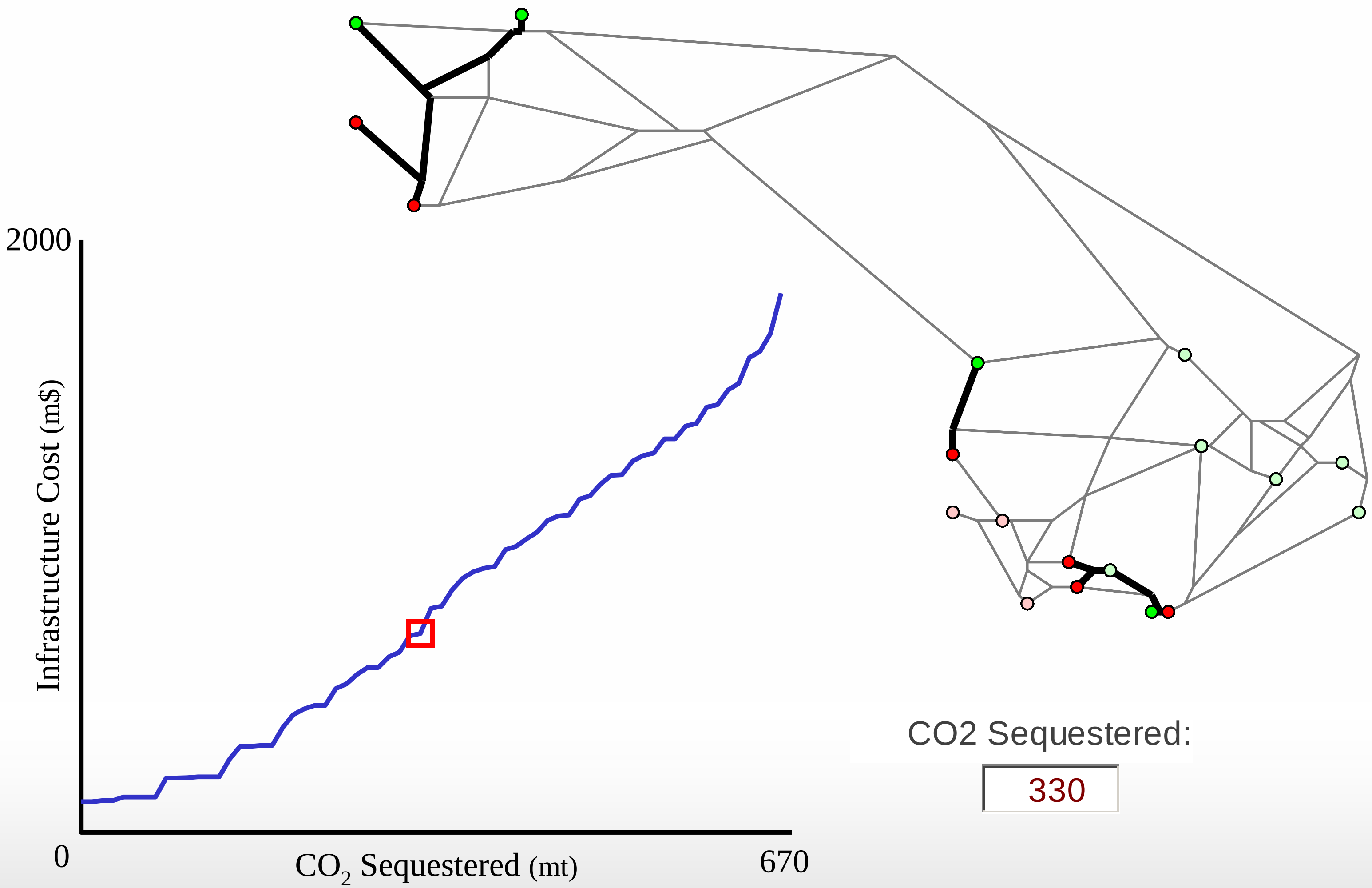
Sequester CO_2 Target Amount



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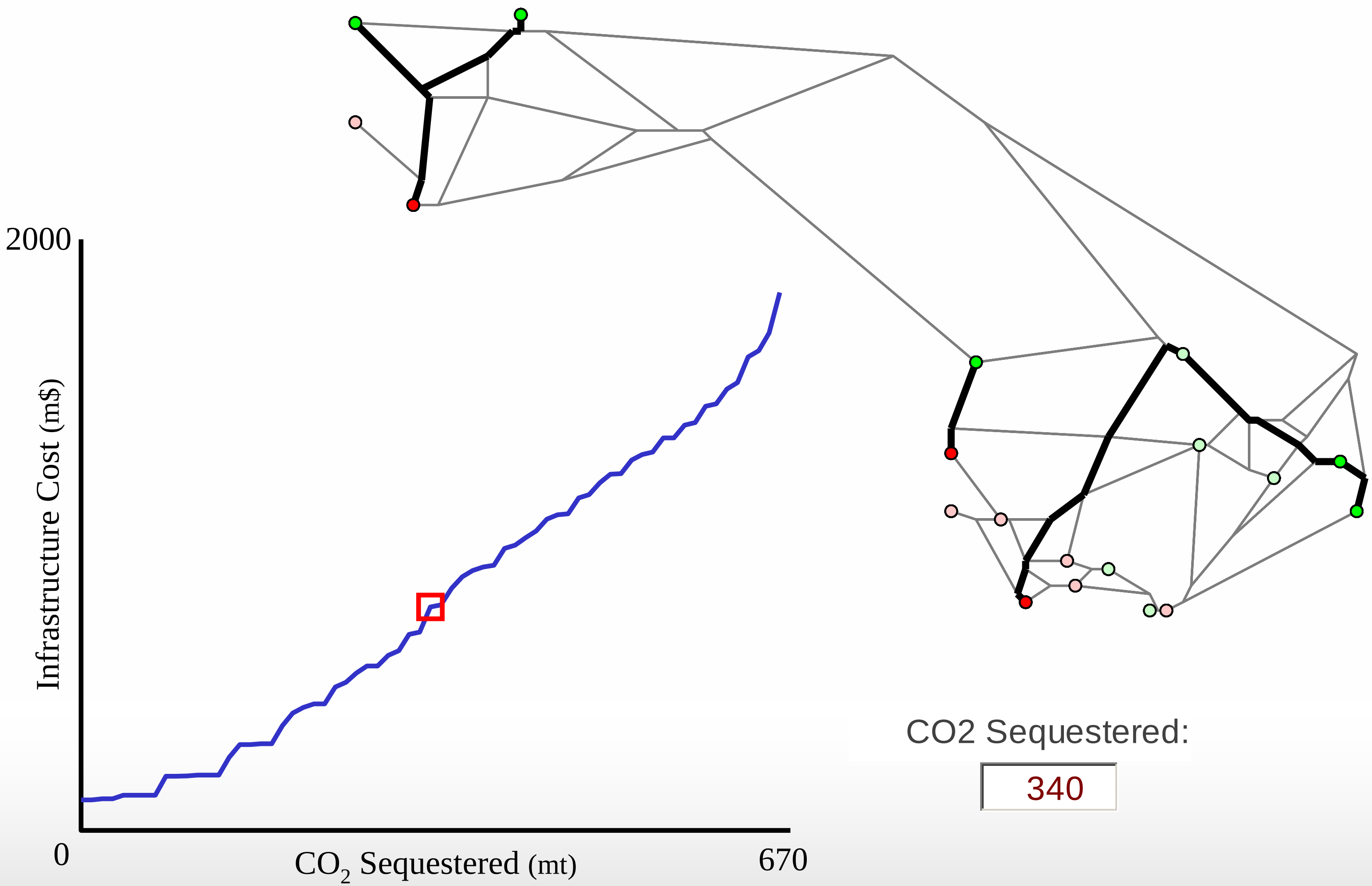
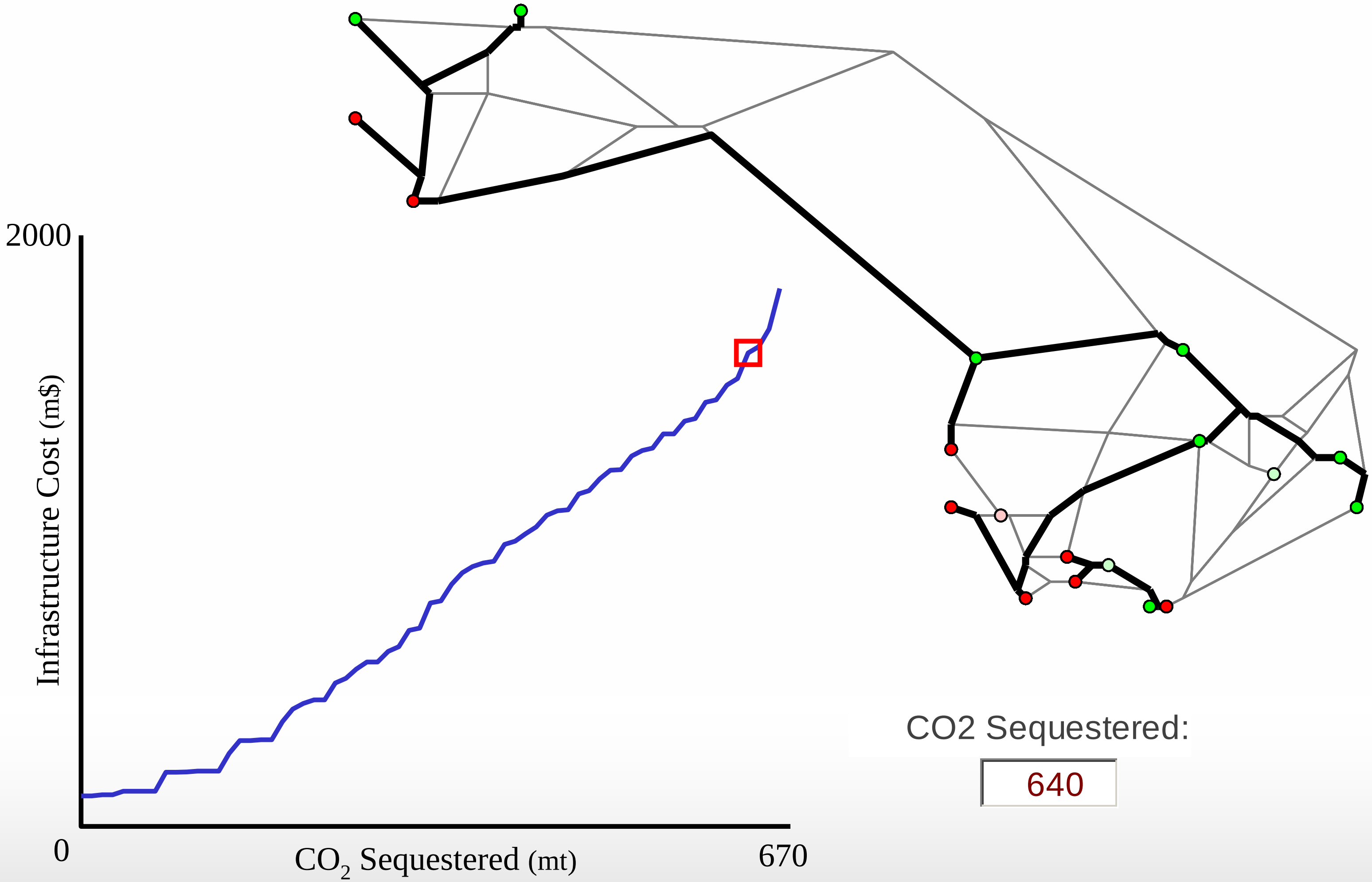
Sequester CO_2 Target Amount

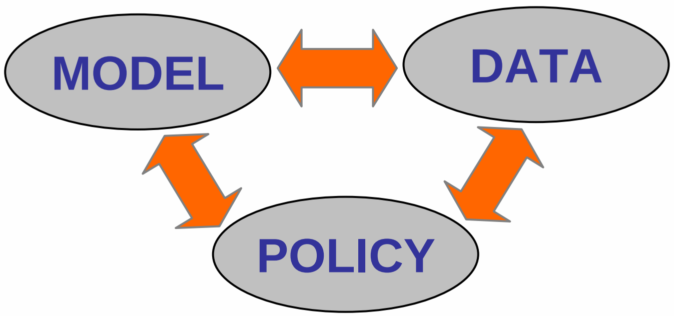


Sequester CO_2 Target Amount

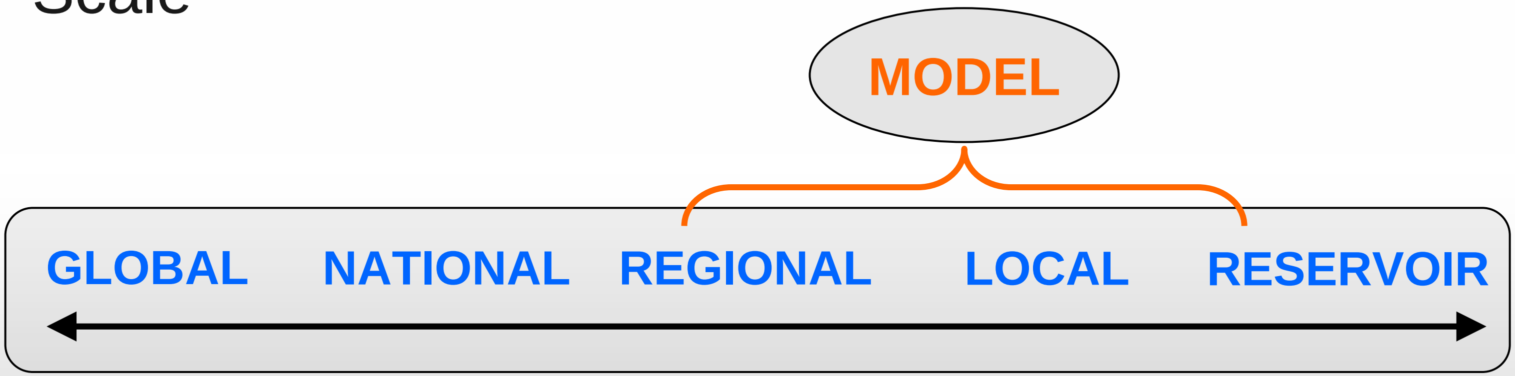


Next Steps in Modeling

- 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/CO_2/electricity transportation
  - coal transportation (~$9) vs. coal waste i.e. CO_2 ($1.8-5)
- Models will provide system overview and drive policy

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