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Title: Secure and sustainable energy infrastructure: The case of CO2 capture, utilization, and storage

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Secure and sustainable energy infrastructure: The case of CO_2 capture, utilization, and storage

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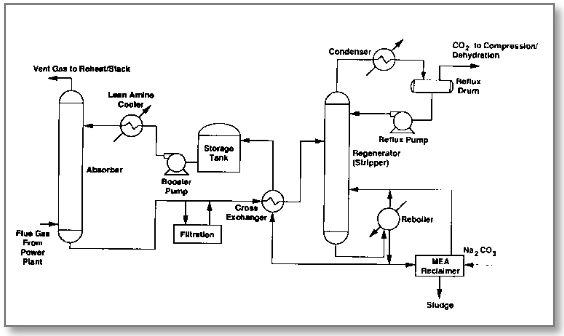
CO_2 Capture, Utilization, and Storage (CCUS)

MENU
CCS
What?
Why?
Scale?
SimCCS
Case studies
Storage
Transport
Capture
La Fin

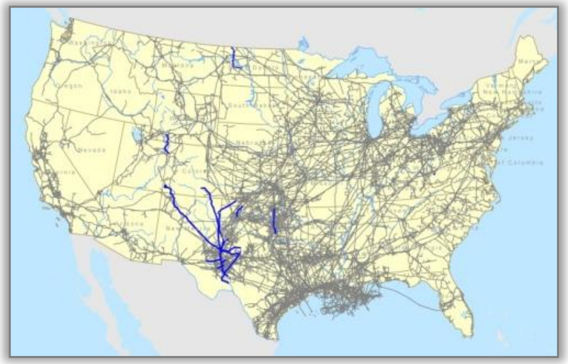
(1) Capture

- capture CO_2 at stationary sources (e.g. power plants, cement works, ammonia, oil refineries)
- compress CO_2 to super-critical state



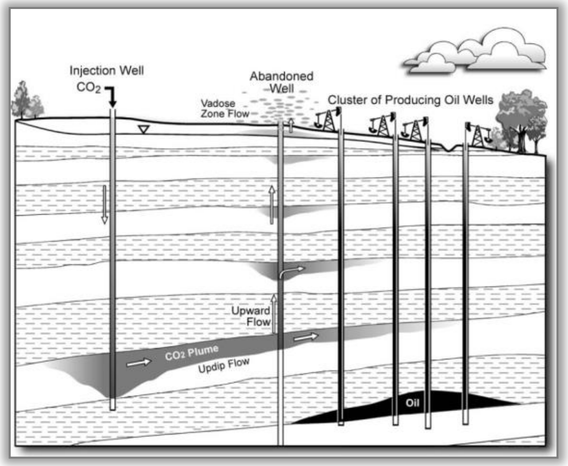
(2) Transport

- pipelines are the only feasible transport mode
- CO_2 source may be located above geologic reservoir



(3) Utilization and/or Storage

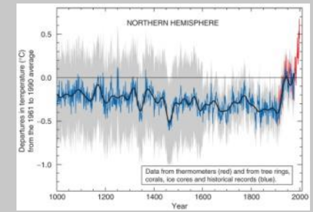
- inject/store CO_2 in geologic reservoirs (e.g. depleted oil fields, deep saline aquifers, unmineable coal seams)
- store/sequester CO_2 for 1,000+ years



CO_2 Mitigation: *“It’s the ~~economy~~ CLIMATE, stupid”…*





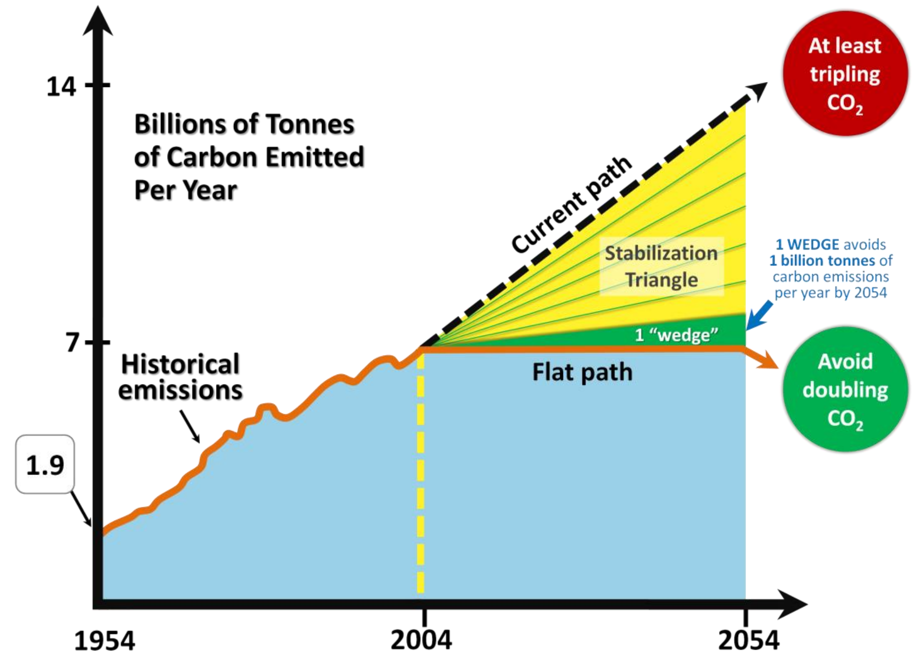
Why CCS?

- technology readily available
- 40+ year experience with CO_2 capture, transport, storage
- immediate and medium-term solution
- makes alternative energy sources cost competitive
- can be implemented without fundamental restructuring of energy and economy infrastructure
- reduce CO_2 footprint of making conventional and non-conventional oil

Scale of CCS Infrastructure

Meaningful CCS

- stabilization wedge
  → abate 1,000 MtC/yr or
  3,670 $MtCO_2$/yr
- U.S. CCS: 920 $MtCO_2$/yr[1]
- manage 1,164 $MtCO_2$/yr[2]
  coal: 2,150 $MtCO_2$/yr[3]
- 245 coal power plants[2,3]



Comparison:

CCS INFRASTRUCTURE MODELING IS CRITICAL

(i) where & (ii) how much CO_2 to capture; (iii) where & (iv) how much CO_2 to inject/store; (v) where, (vi) size, & (vii) networking of pipelines; (viii) optimally allocate CO_2

[1] 25% of world electricity (EIA 2010); [2] ~27% energy penalty (Simbeck and MacDonald 2000); [3] eGRID 2007; [4] 25°C & 2,000 psi

SimCCS: Scalable Infrastructure Model for CCS

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*
  - **SimCCS**[CAP]: *cap-and-trade environment*
  - **SimCCS**[PRICE]: *CO_2 tax*
  - **SimCCS**[TIME]: *infrastructure evolution*

OPTIMIZATION ENGINE

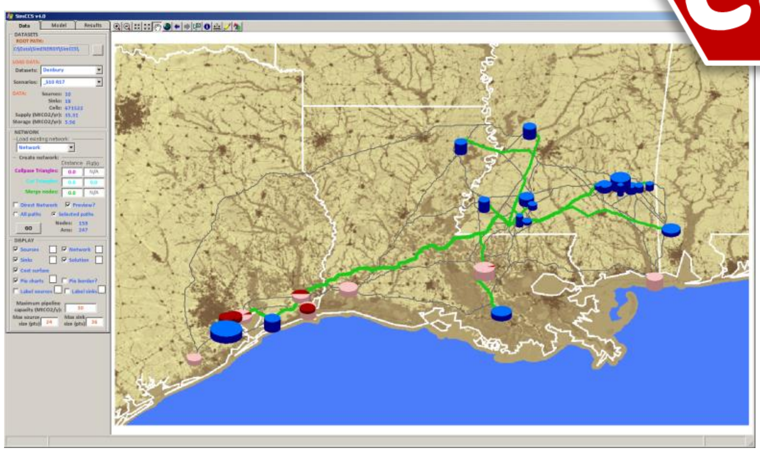
Cost to open source, capture CO_2 + Cost to purchase land, construct pipeline, and transport CO_2 + Cost to open reservoir, inject CO_2

(1)	$x_{ij} - \sum_{d \in D} {}_{\max} Q^p_{ijd} y_{ijd} \le 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be less than maximum pipeline capacity
(2)	$x_{ij} - \sum_{d \in D} {}_{\min} Q^p_{ijd} y_{ijd} \ge 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be more than minimum pipeline capacity
(3)	$\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0$	$\forall i \in I$	CO_2 flow leaving a node must equal inflow
(4)	$a_i - Q^s_i s_i \le 0$	$\forall i \in S$	CO_2 captured at a source must not exceed supply
(5)	$b_j - Q^r_j r_j \le 0$	$\forall j \in R$	CO_2 stored at a sink must not exceed capacity
(6)	$\sum_{i \in S} a_i \ge T$		Target amount of CO_2 to store or sequester
(7)	$\sum_{d \in D} y_{ijd} \le 1$	$\forall i \in I, j \in N_i$	Only one pipeline can be built between nodes

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

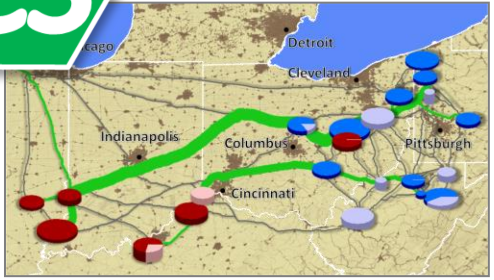
$x_{ij} \ge 0 \quad \forall i, j \in N_i$
$a_i \ge 0 \quad \forall j \in S$
$b_j \ge 0 \quad \forall j \in R$
Non-negativity constraints

INTERFACE



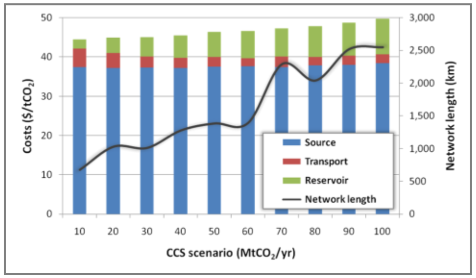
- custom/open-source GIS, network generation, model building

POLICY ANALYSIS

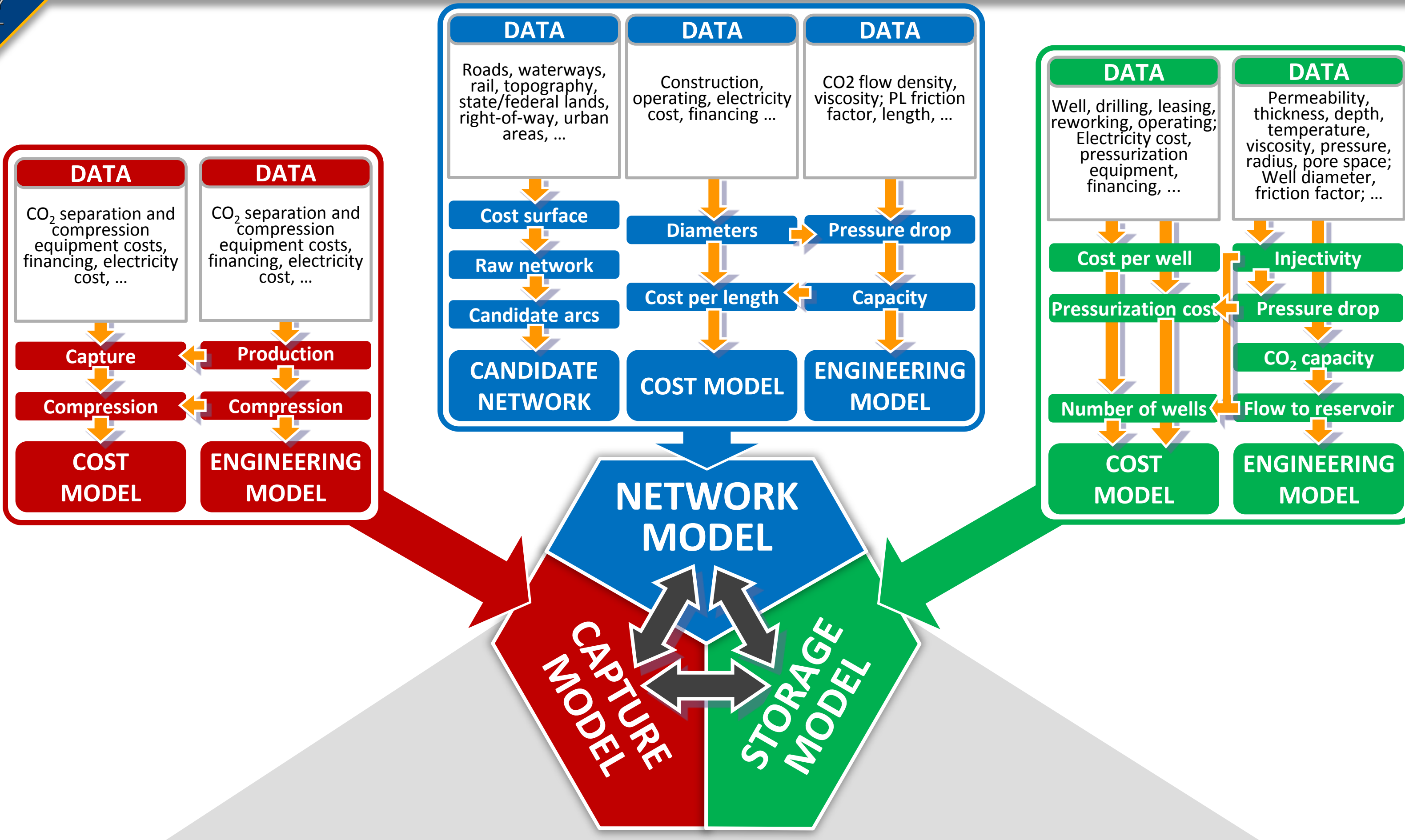


Spatial analysis

Economics & engineering



SimCCS: Scalable Infrastructure Model for CCS



COSTS	SPATIAL DEPLOYMENT	CO_2 FLOWS	GENERAL
Cost to deploy CCS infrastructure	**Where to capture and/or release CO_2**	**CO_2 amount to be captured at each source**	Amount of CO_2 cost-effectively sequestered
Capture, transport, and storage costs	Location of capture-ready CO_2 sources	**How much CO_2 should be stored in each reservoir**	Scale of CCS infrastructure
Carbon tax ($/tonne)	**Which reservoirs should inject/store CO_2**	**CO_2 pipeline capacities**	Policy implications
Cap and trade pricing	**Dedicated CO_2 pipeline *network***	**CO_2 allocation between sources and reservoirs**	Tradeoff between capture, transport, and storage

$SimCCS^{PRICE}$: mixed integer-linear program

$$\overbrace{\sum_{i\in S}(F_i^s s_i + V_i^s a_i)}^{(a)} + \overbrace{\sum_{i\in I}\sum_{j\in N_i}\sum_{c\in C}\alpha_{ijc}^p p_{ijc} + \sum_{i\in I}\sum_{j\in N_i}\sum_{c\in C}\beta_{ijc}^p y_{ijc}}^{(b)} + \overbrace{\sum_{j\in R}(F_j^r r_j + F_j^w w_j + V_j^r b_j)}^{(c)} + \overbrace{\sum_{i\in S}F^{tax}(Q_i^s - a_i)}^{(d)} \quad (1)$$

Costs: Capture, transport, storage, and tax

Subject to:

$$x_{ij} \le \sum_{c\in C} p_{ijc} \qquad \forall i\in I, \forall j\in N_i \quad (2)$$

CO_2 flow

$$Q_c^{p} y_{ijc} \le p_{ijc} \le Q_c^{p'} y_{ijc} \qquad \forall i\in I, \forall j\in N_i, \forall c\in C \quad (3)$$

Pipeline capacity

$$\sum_{j\in N_i} x_{ij} - \sum_{j\in N_i} x_{ji} = \begin{cases} a_i & if\ i\in S \\ -b_i & if\ i\in R \\ 0 & otherwise \end{cases} \qquad \forall i\in I \quad (4)$$

CO_2 mass balance

$$a_i \le Q_i^s s_i \qquad \forall i\in S, \forall g\in G_i \quad (5)$$

CO_2 capture

$$b_j \le Q_j^w w_j \qquad \forall j\in R \quad (6)$$

CO_2 storage

$$w_j \le P_j^w r_j \qquad \forall j\in R \quad (7)$$

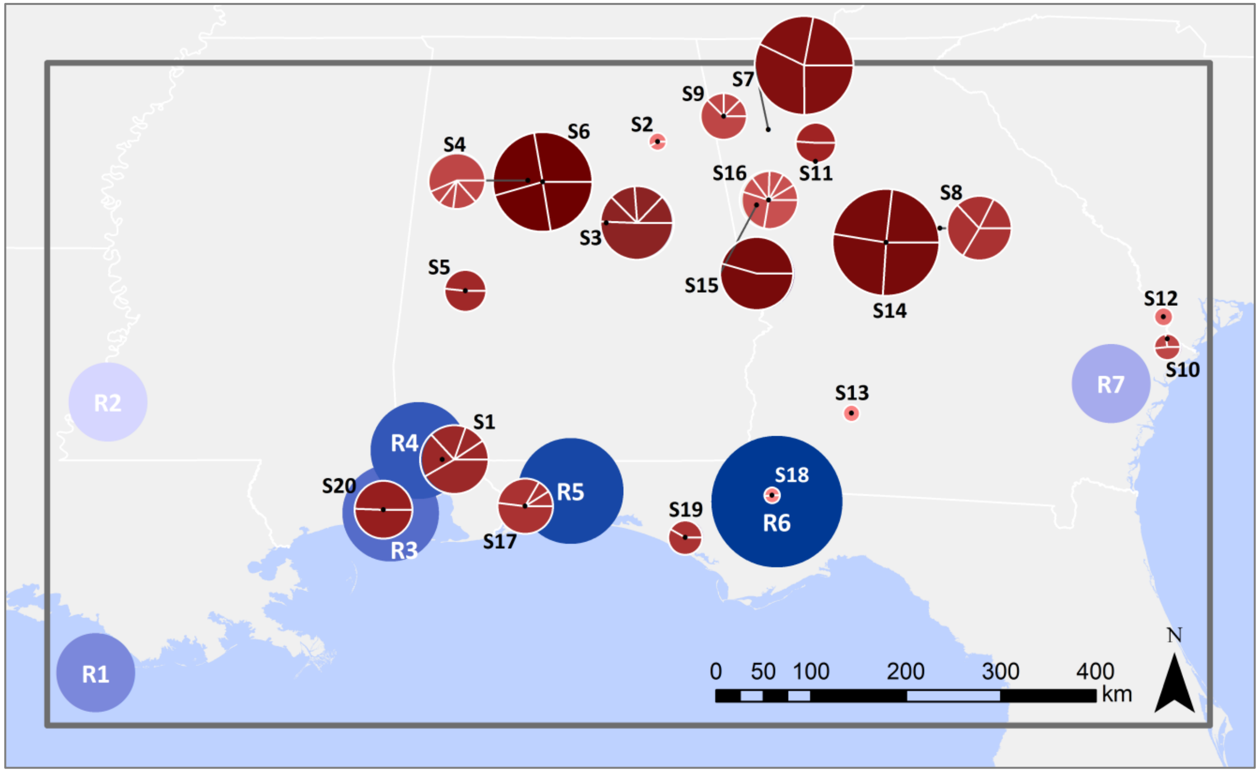
Injection wells

$y_{ijc} \in \{0,1\}$	$\forall i\in I, \forall j\in N_i, \forall d\in D$	(8)
$s_i \in \{0,1\}$	$\forall i\in S, \forall g\in G_i$	-
$r_j \in \{0,1\}$	$\forall j\in R$	-
$w_j \in \{0,1,2,\ldots,n\}$	$\forall j\in R$	-
$x_{ij} \ge 0$	$\forall i\in I, \forall j\in N_i$	-
$a_i \ge 0$	$\forall i\in I$	-
$b_j \ge 0$	$\forall j\in R$	-

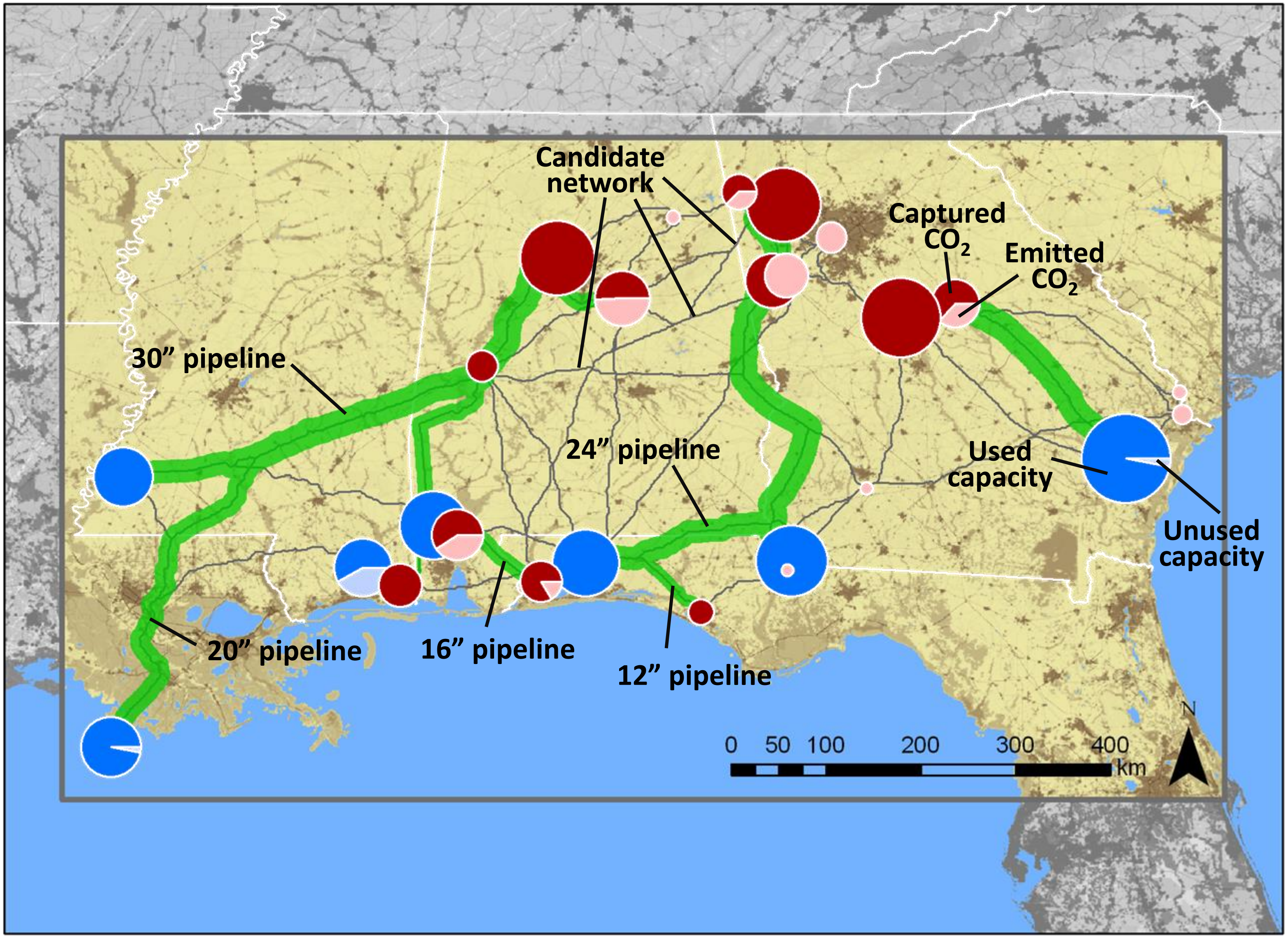
Variable definitions and bounds

Southern Company (SoCo)

- 10 year business plan and CO_2 emissions strategy
- 20 coal-fired plants, 156 $MtCO_2$/yr emissions
- 65 individual boilers→ boiler level accuracy
- capture costs: \$46-102/tCO_2 (plant) & \$41-166/tCO_2 (boiler)
- storage: 3.4 $GtCO_2$ in 7 sinks, 113 $MtCO_2$/yr over 30 years
- storage costs: \$3.78-8.60/tCO_2

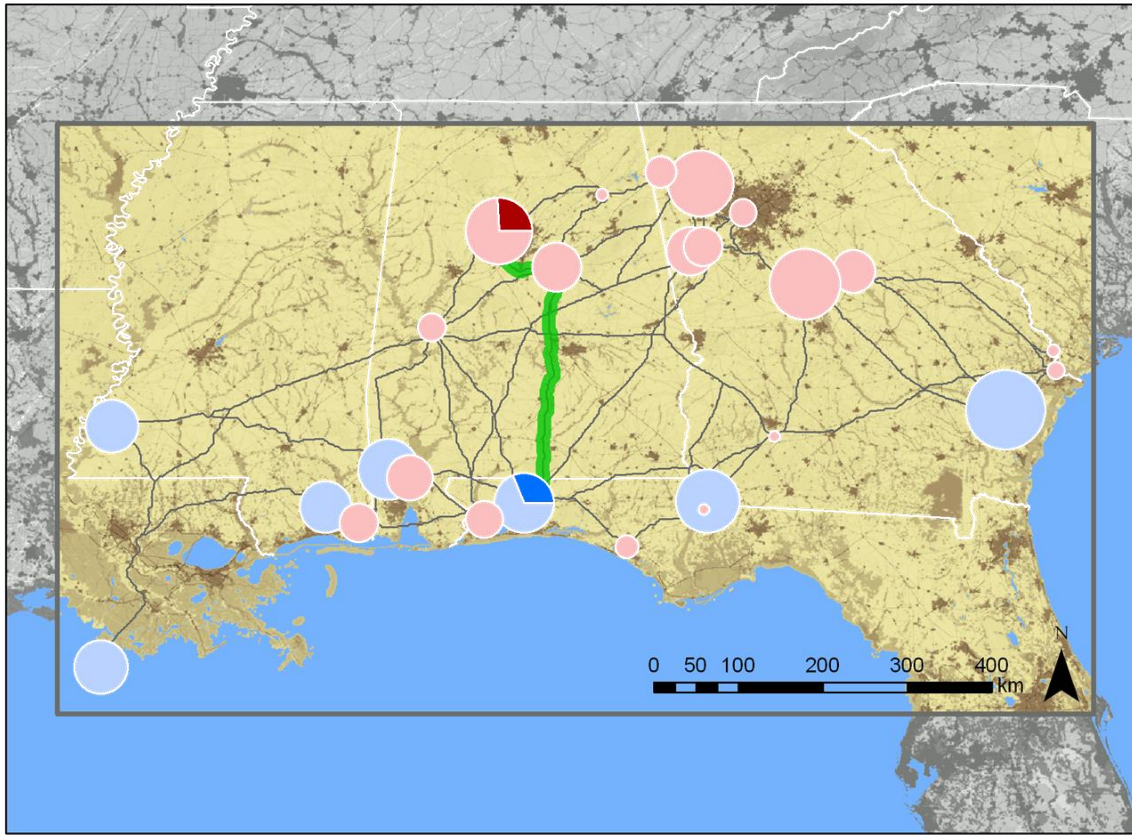


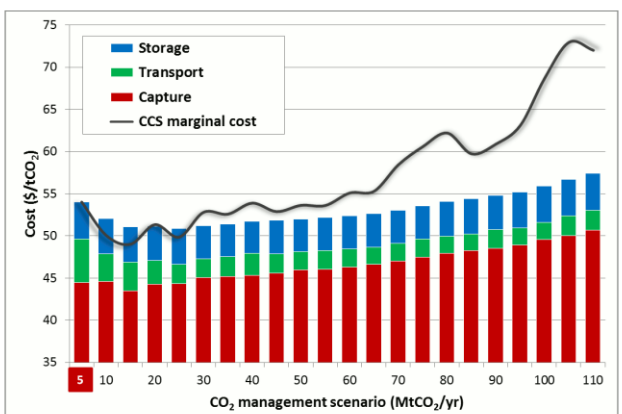
SoCo: example infrastructure

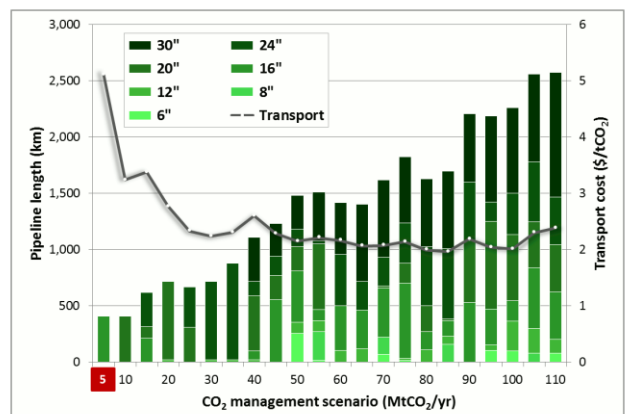


* **Middleton et al. (2012)** The cross-scale science of CO_2 capture and storage: from pore scale to regional scale, *Energy & Environmental Science 5* , 7328-7345.

SoCo: 5 to 110 $MtCO_2$/yr scenarios







China: Ordos Basin

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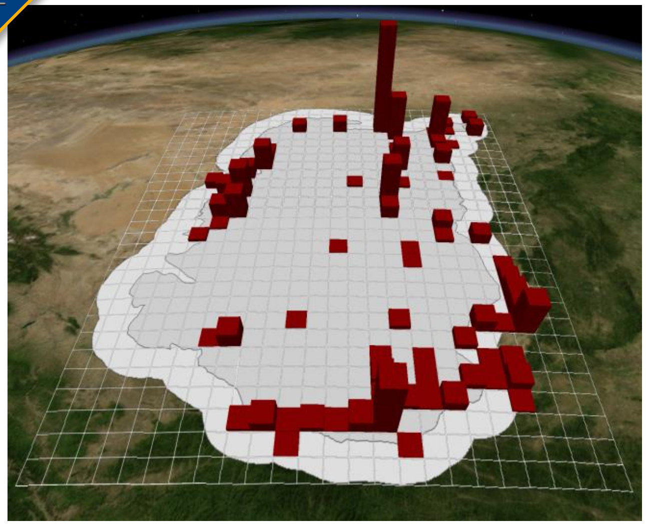
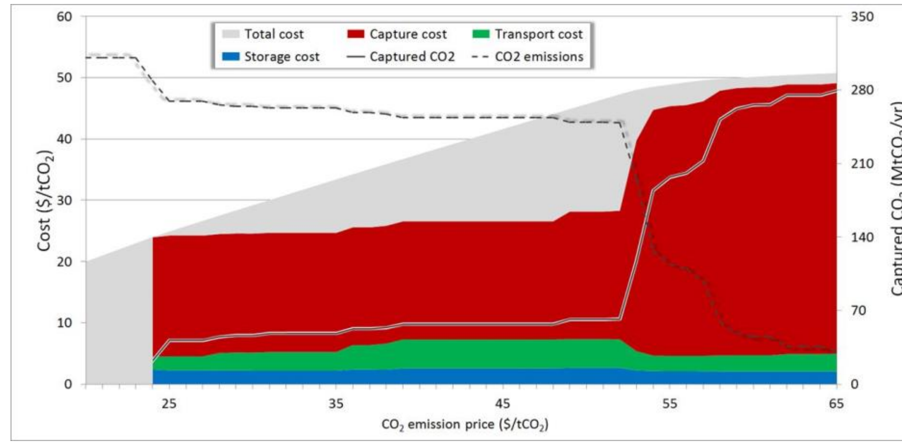
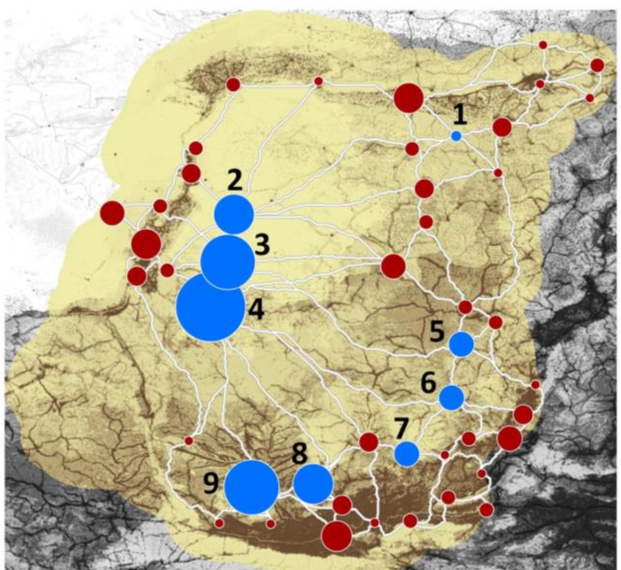
- multiple CCS scenarios driven by (a) CO_2 cap and (b) CO_2 emission prices
- understand how CO_2 capture, transport, and storage research interacts



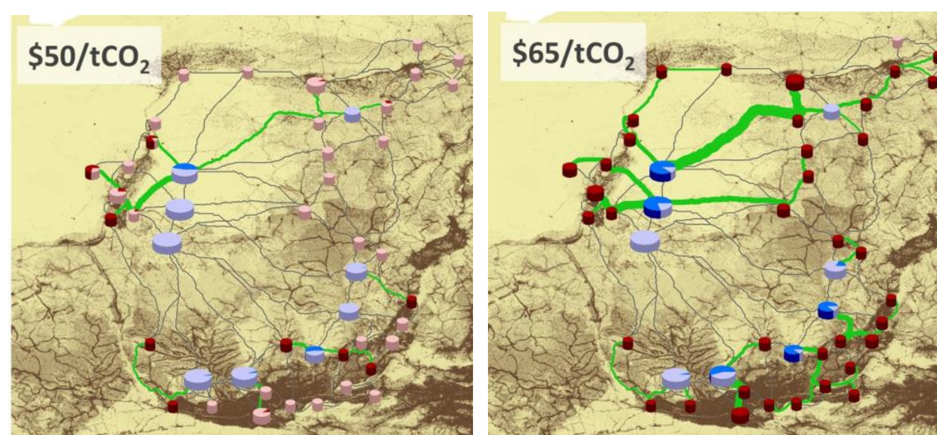
"Global" perspective of Ordos CO_2 emissions



Infrastructure response (cost & engineering) to a CO_2 tax



Candidate transport network, sources, & sinks

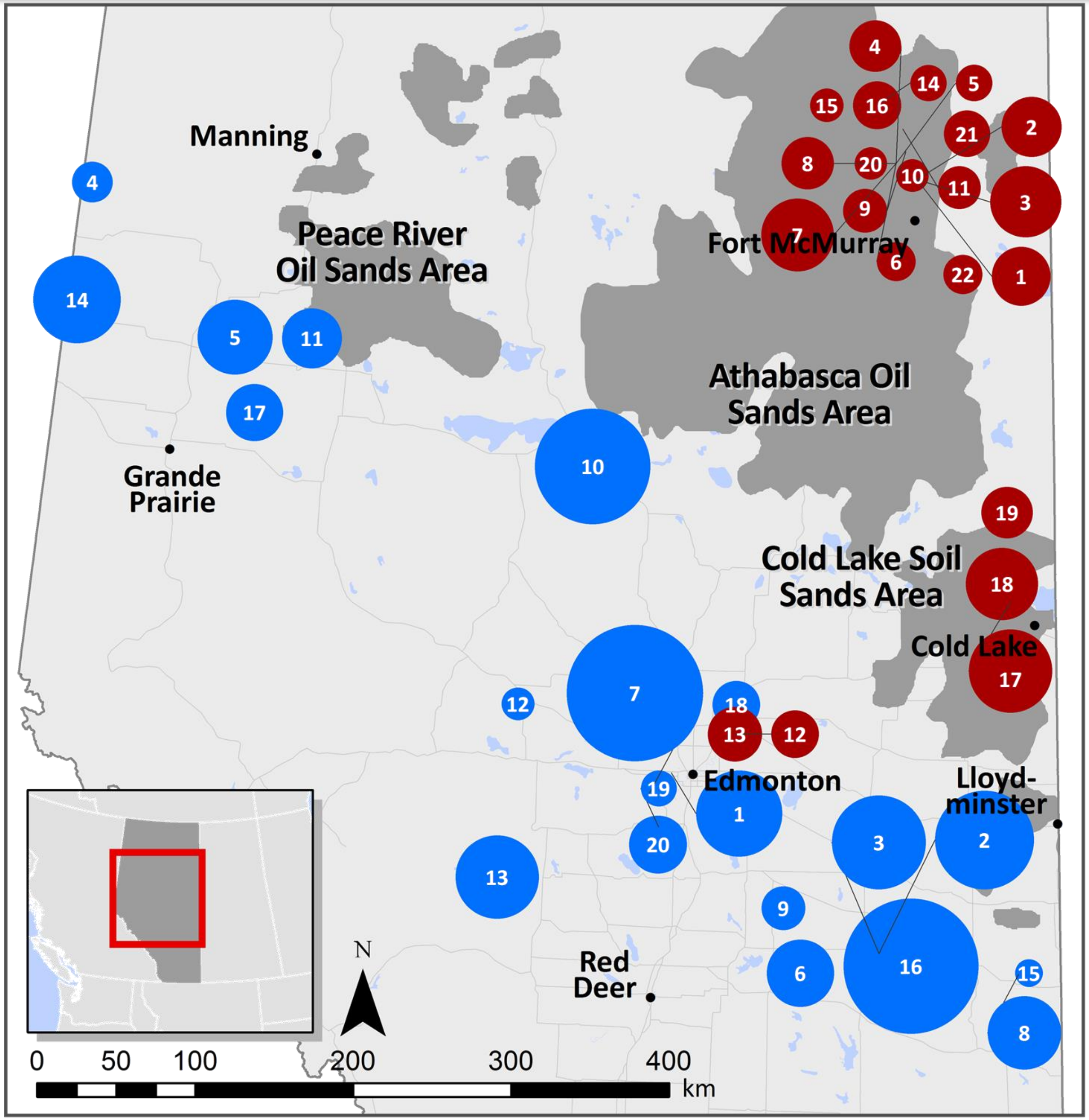


Geospatial infrastructure comparison for different CO_2 tax rates

Oil sands: overview

- 22 sources; 39 $MtCO_2/yr$
- Surface mining and *in situ* extraction
- CO_2 life cycle analysis

- 20 reservoirs
- Based on acid gas injection observations
- Storage capacities, injection rates, and site-wide economics



* **Middleton and Brandt (2013)** Using infrastructure optimization to reduce greenhouse gas emissions from oil sands extraction and processing, *Environmental Science & Technology 47*, 1735-1744.

Oil sands: candidate network

- generate candidate network linking sources and sinks

candidate network

A Lake

B First Nation

C River

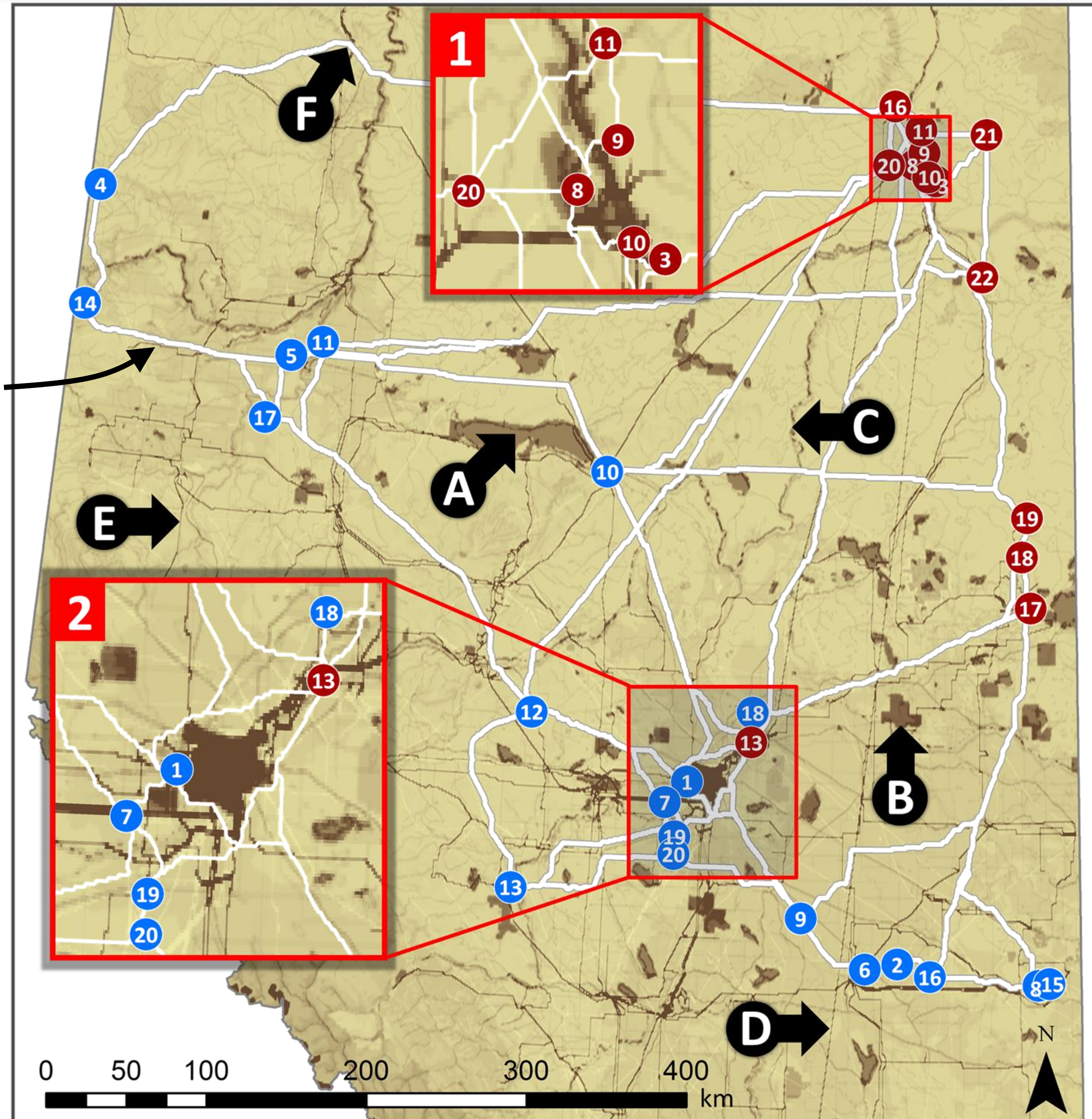
D Transmission line

E Road

F Pipeline ROW

COST SURFACE

Low High



Oil sands: response to uncertainty

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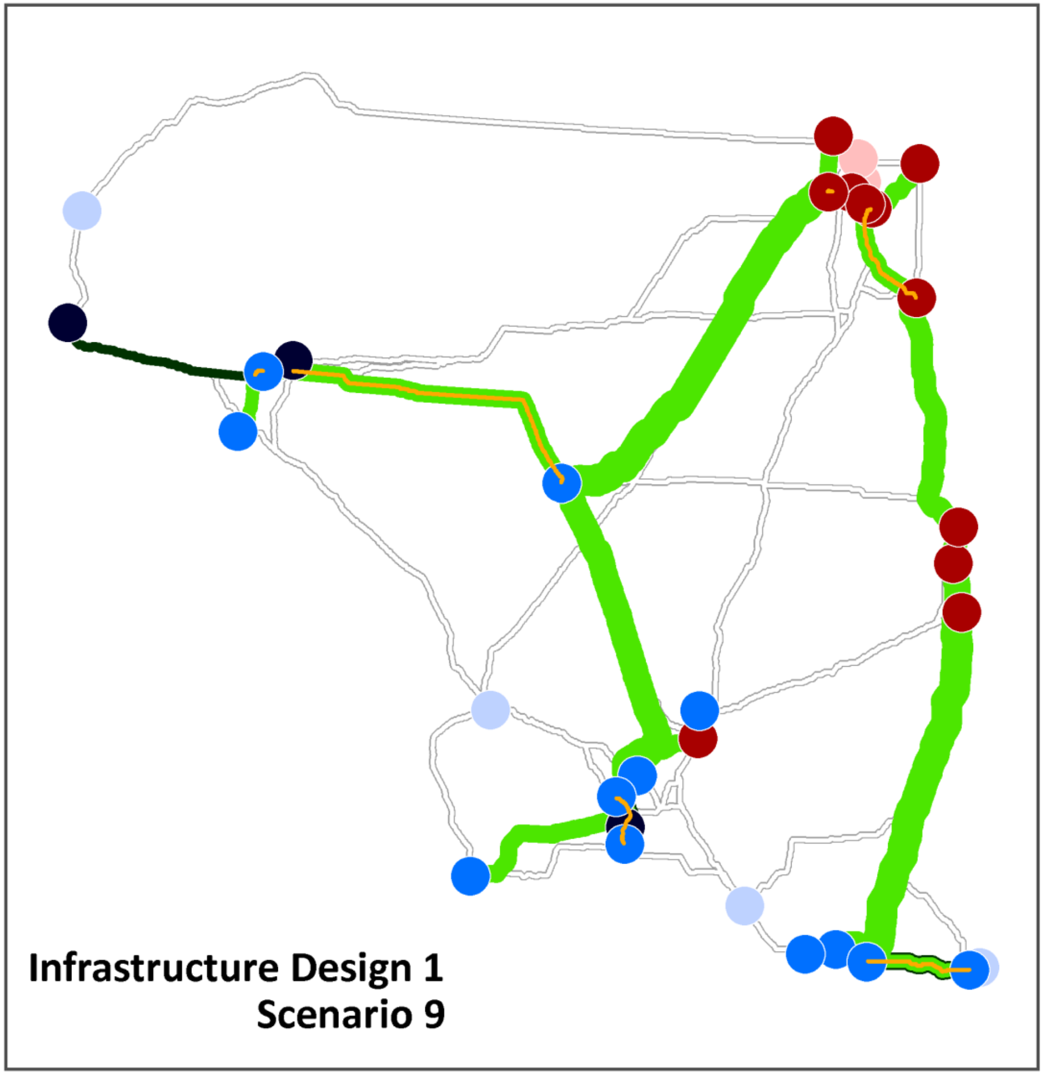
Impact

- open new reservoirs
- drill and operate new injection wells
- construct pipelines along new routes (includes ROW cost)
- build duplicate pipelines (enhanced *SimCCS* model)



* **Middleton et al. (2012)** Effects of geologic reservoir uncertainty on CO_2 transport and storage infrastructure, *International Journal of Greenhouse Gas Control 8*, 132-142.

Uncertainty & system design : risk & economic impact

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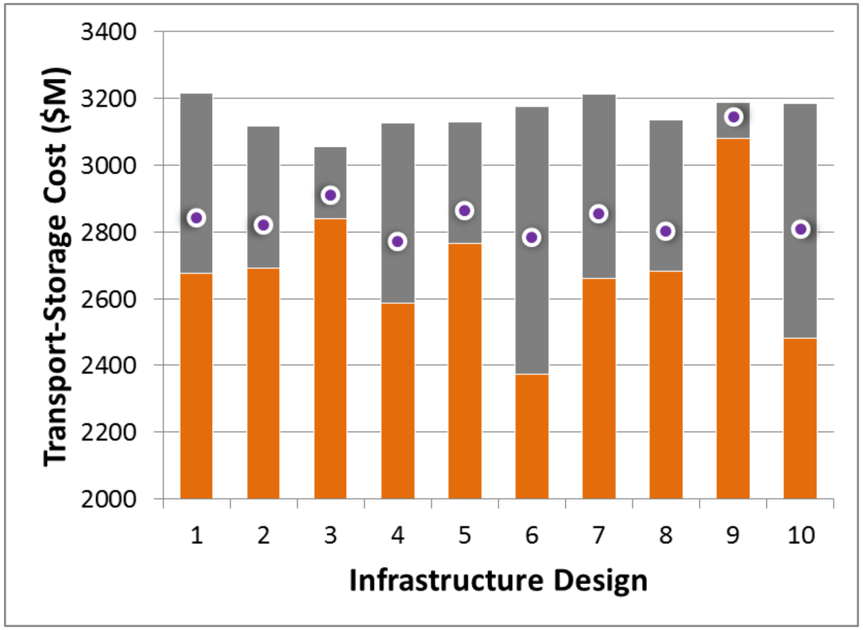
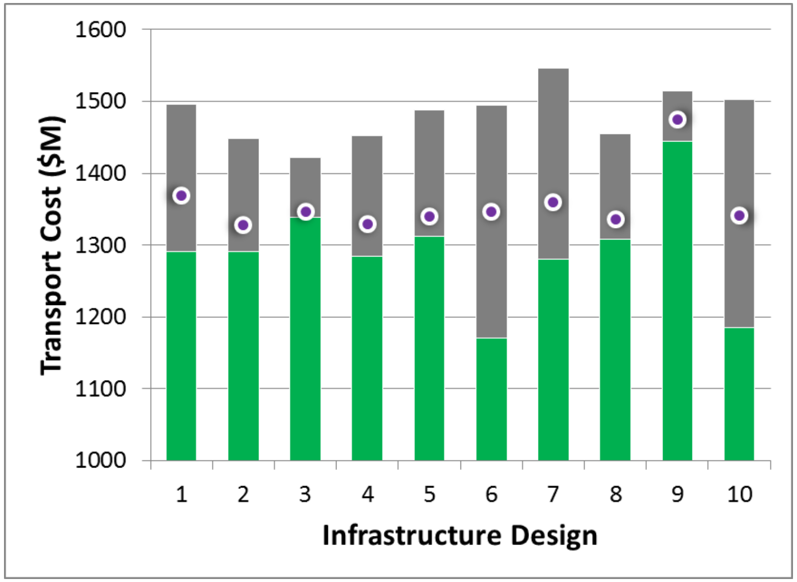
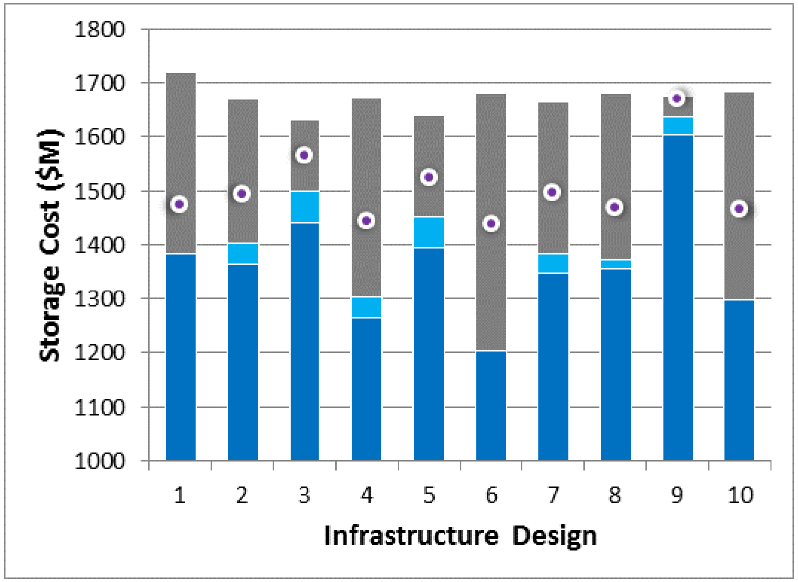
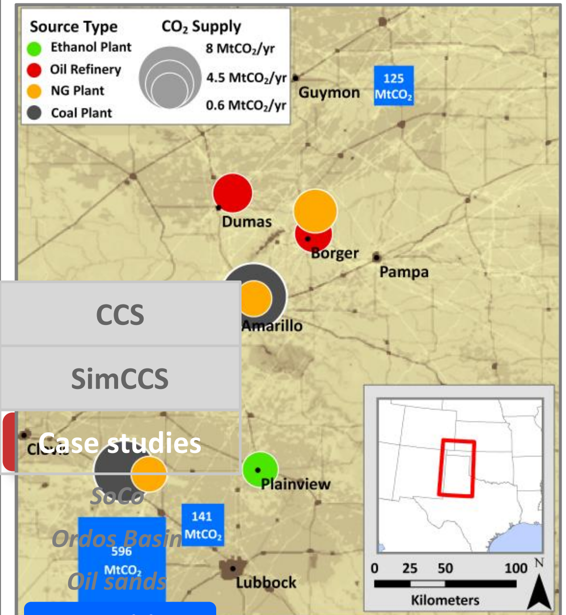
CO_2 Transport & storage

- capture rate and costs do not vary
- best, worst, expected outcomes
- best: design 6?
- worst: design 9?
- interesting: designs 3 & 5?







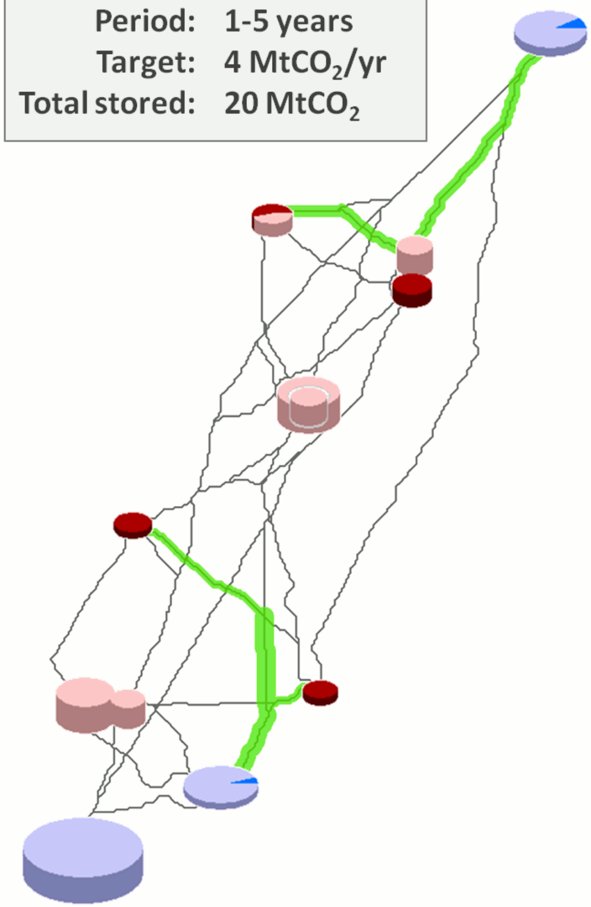


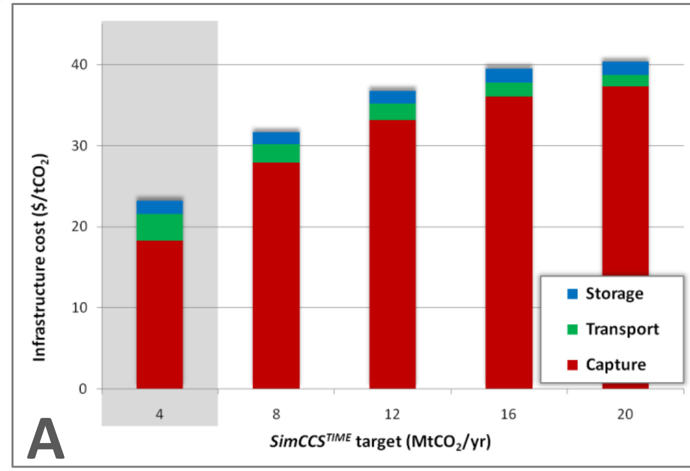
...handle

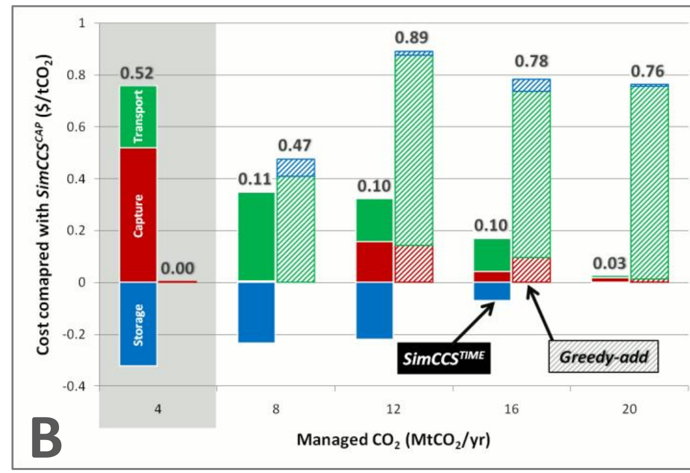
...s (2 biorefineries, 2 ..., 2 coal and 3 natural ... producing 21

... on reservoirs (depleted oil fields) with 862 $MtCO_2$ capacity

Period: 1-5 years
Target: 4 $MtCO_2$/yr
Total stored: 20 $MtCO_2$







SimCCS^{TIME}

- *spatial optimization framework for* CO_2 capture and storage (CCS) infrastructure (capturing, transporting, injecting/storing CO_2) through *multiple time periods*
- deploys CCS *networks* to meet a CO_2 *cap* (i.e., cap-and-trade) or in response to a *price/tax* to emit CO_2
- *scientists*, *stakeholders*, *policy makers*, general *public*

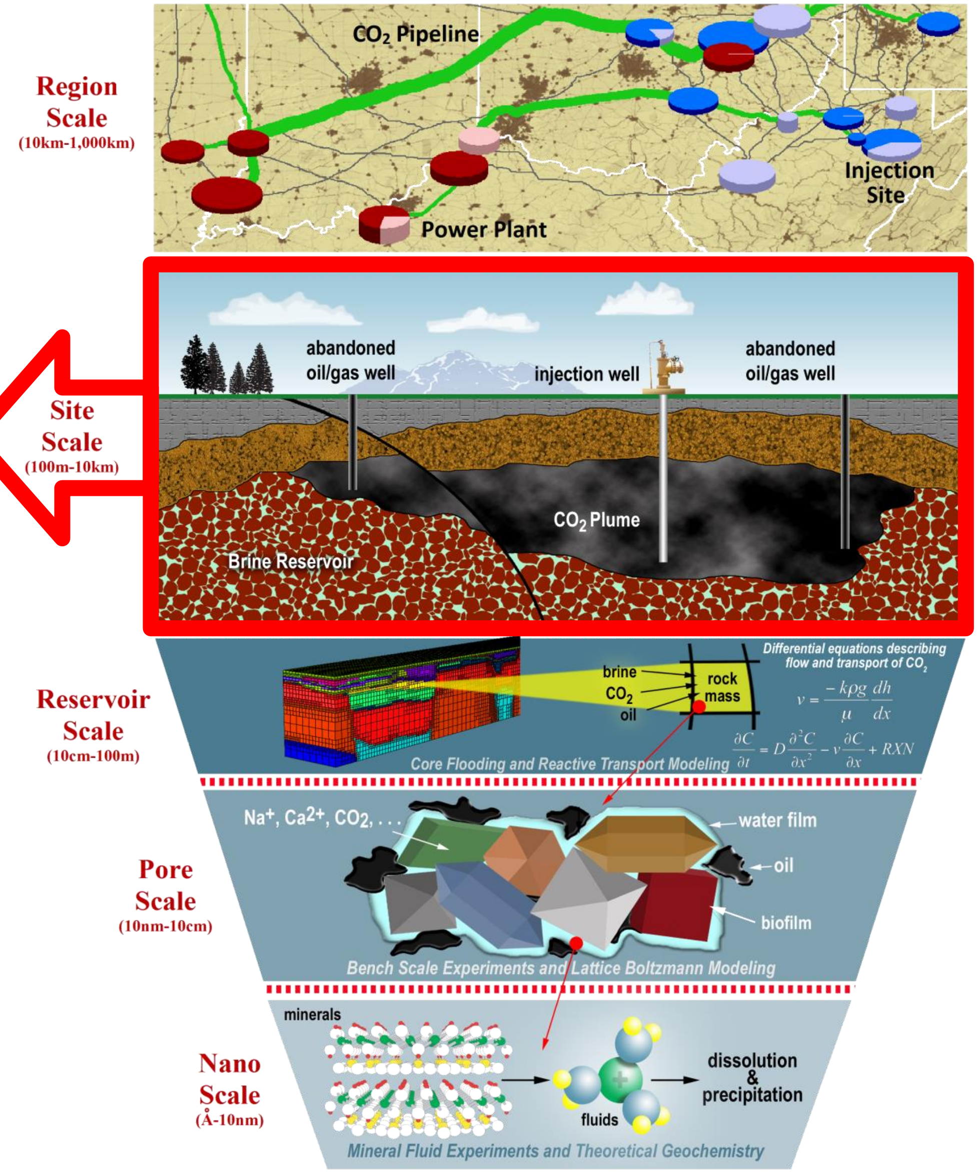
Scenario

- *overbuilds infrastructure* (e.g., pipelines, capture) in early periods to achieves *long-term economies of scale*
- *CCS costs rise through time* as more expensive CO_2 sources are brought online, *transport costs fall* through increased utilization (Chart A)
- *minimizes costs* across all time periods (Chart B)

* **Middleton et al. (2012)** A dynamic model for optimally phasing in CCS infrastructure, *Environmental Modelling & Software 37*, 193-205.

CO_2 injection and storage

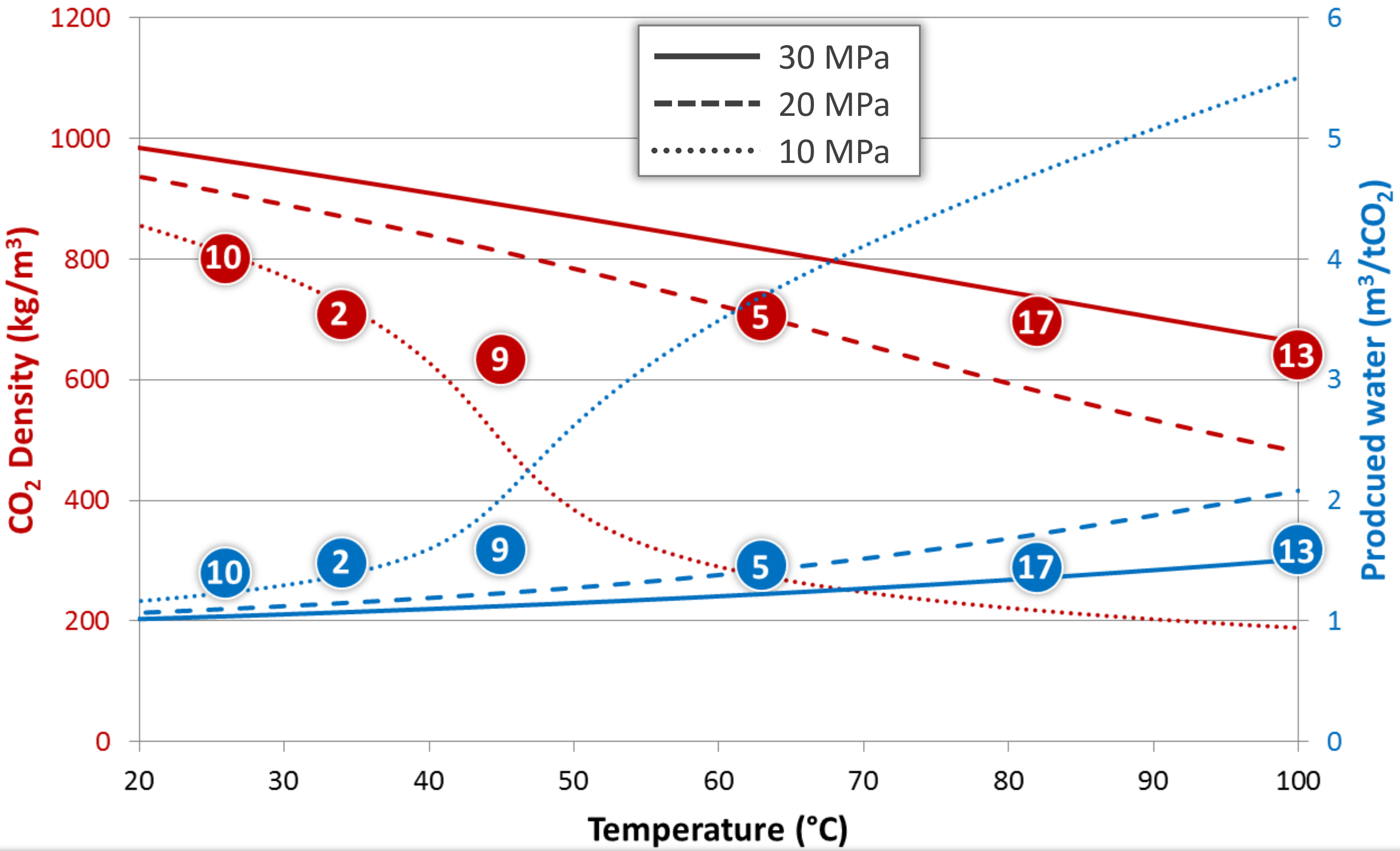
- **inputs:** formation depth, thickness, porosity, permeability, temp-erature, brine chemistry
- **computationally-efficient models:** based on fine-physics mechanistic (or process) models
- **outputs:** injectivity, well spacing storage capacity, and CO_2 plume charact-eristics
- **economics:** permitting, injection/production wells, pumping, distribution pipelines, pore space rights, monitoring, water treatment…



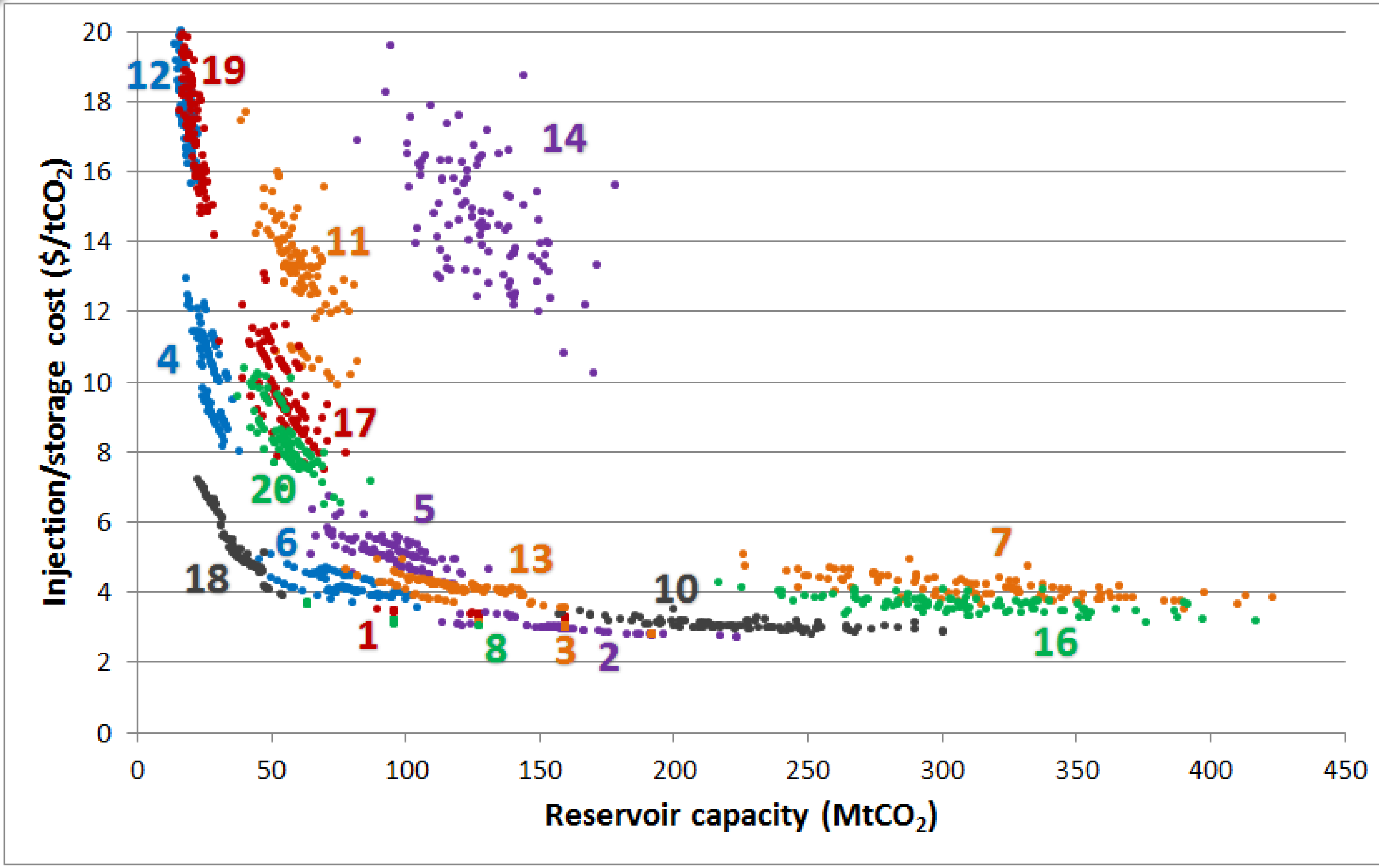
* **Middleton et al. (2012)** The cross-scale science of CO_2 capture and storage: from pore scale to regional scale, *Energy & Environmental Science 5* , 7328-7345.

Extracted water

- enhance storage, CO_2 plume management, reduce seismicity risks
- function of depth/pressure and temperature
- significant impact on engineering and costs



CO_2 storage uncertainty/heterogeneity



UNCERTAINTY: formation thickness, permeability, and porosity

EFFECT: available volume, injectivity, well spacing

IMPACT: storage capacity, injection-storage cost

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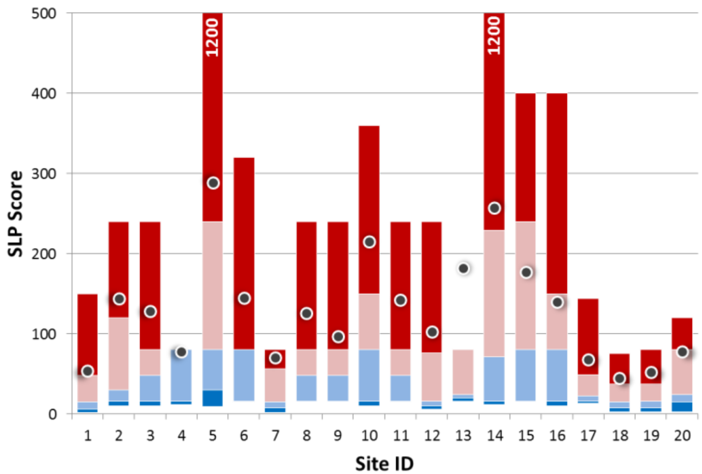
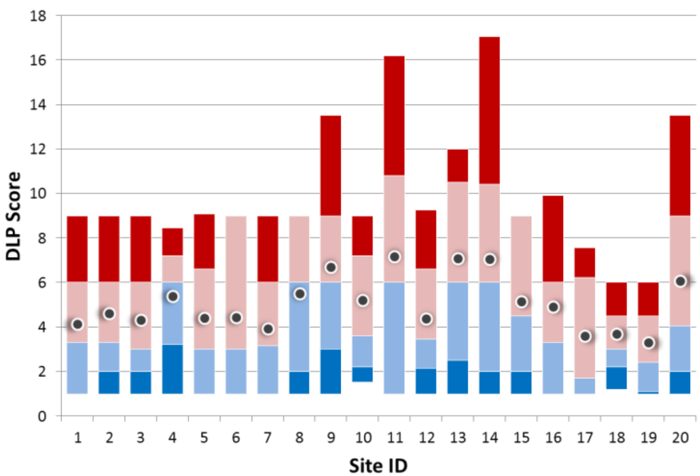
Leakage potential: shallow (SLP) and deep (DLP)[1,2]

- database of ~460,000 wells in Alberta





SCORE DISTRIBUTION

		DLP			
		LOW	MEDIUM	HIGH	EXTREME
SLP	LOW	16.2	25.8	14.5	9.11
	MEDIUM	3.51	9.24	7.86	3.99
	HIGH	1.02	2.48	1.87	0.77
	EXTREME	0.65	1.24	1.32	0.41

[1] **Watson and Bachu (2007)** Evaluation of the Potential for Gas and CO_2 Leakage along Wellbores, SPE Paper #: 106817

[2] **Watson and Bachu (2008)** Identification of Wells with High CO_2-Leakage Potential in Mature Oil Fields Developed for CO_2-Enhanced Oil Recovery, SPE Paper #: 112924

Coupled CO_2 sequestration/EOR systems

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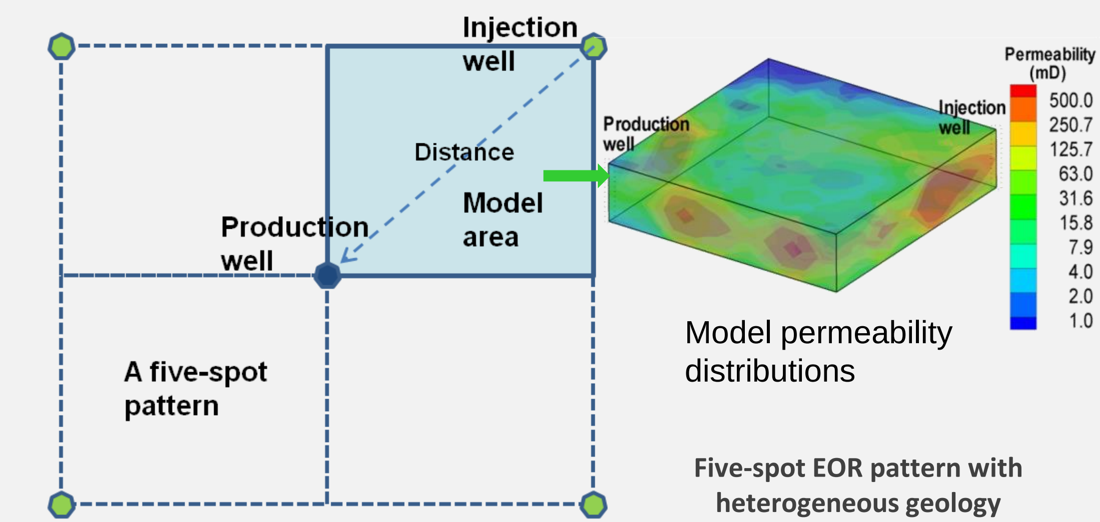
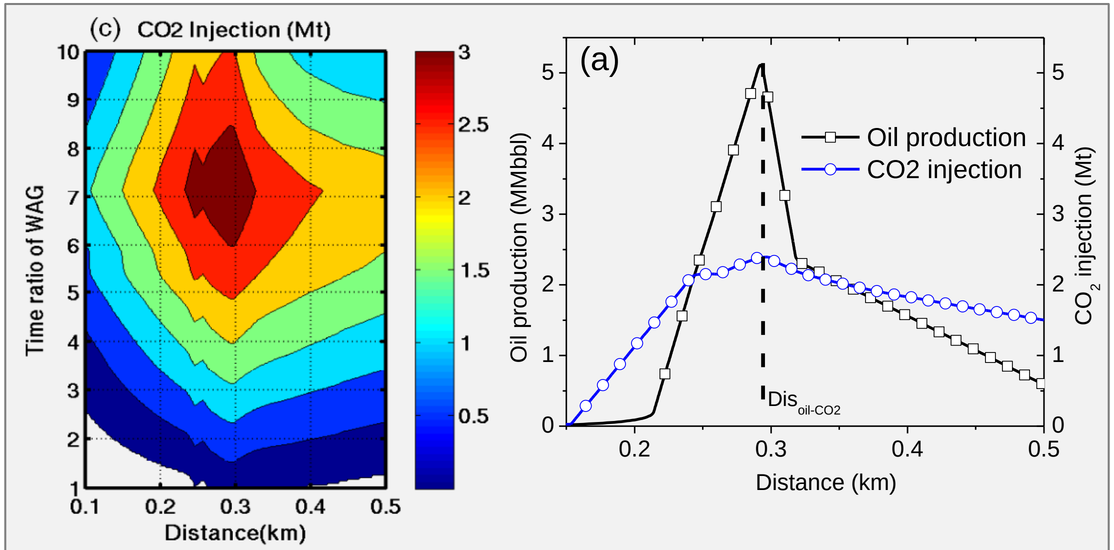
- framework to co-estimate CO_2 storage and oil production
- optimize site engineering including WAG ratio and well spacing
- formally track uncertainty and parameter importance
- economics



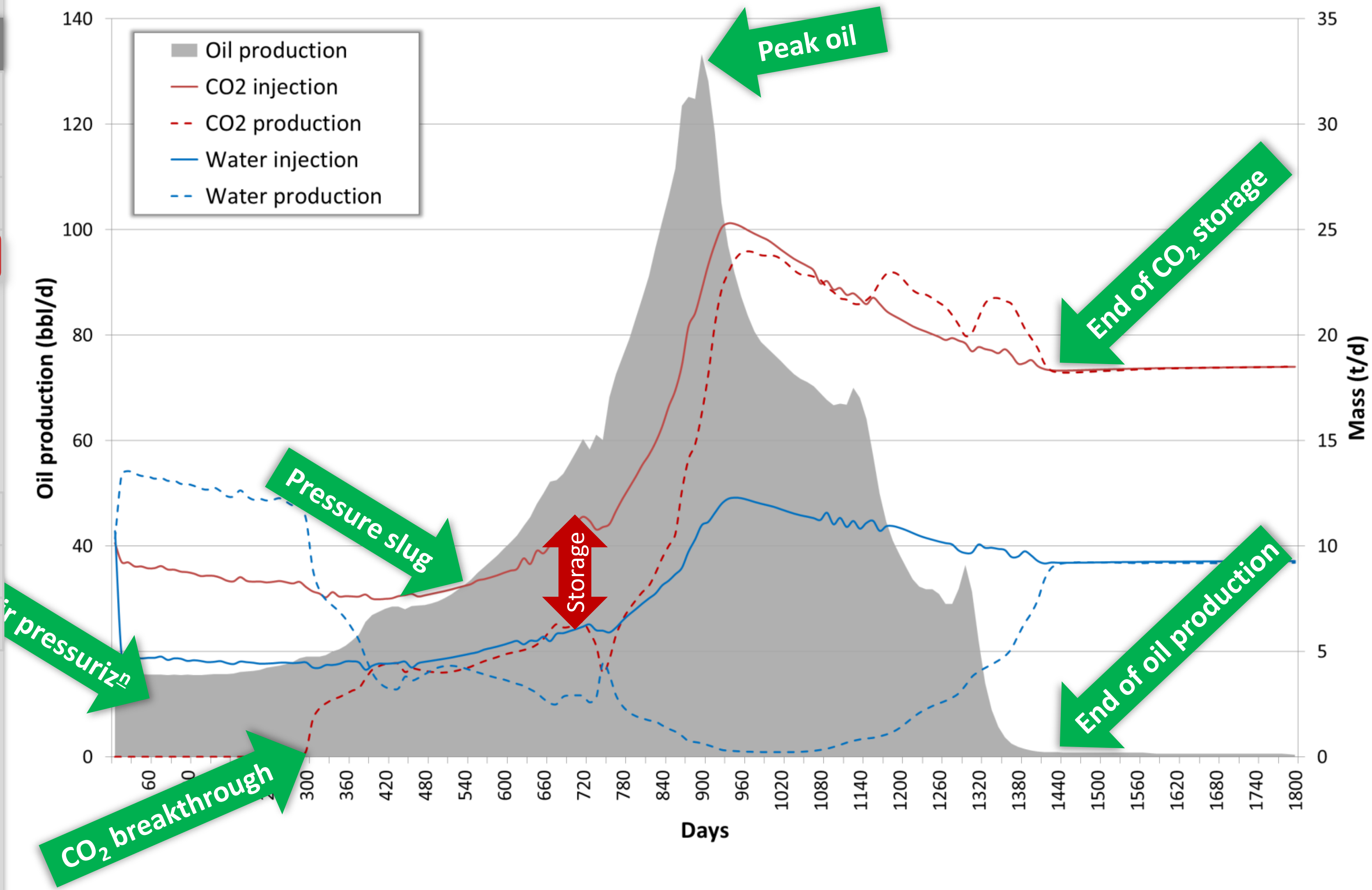
Five-spot EOR pattern with heterogeneous geology



Optimal combination of injection-production distance and WAG ratio

Dai, Middleton, *et al*. (2014) An integrated framework for optimizing CO_2 sequestration and enhanced oil recovery, *Environmental Science & Technology Letters 1*, 49-54.

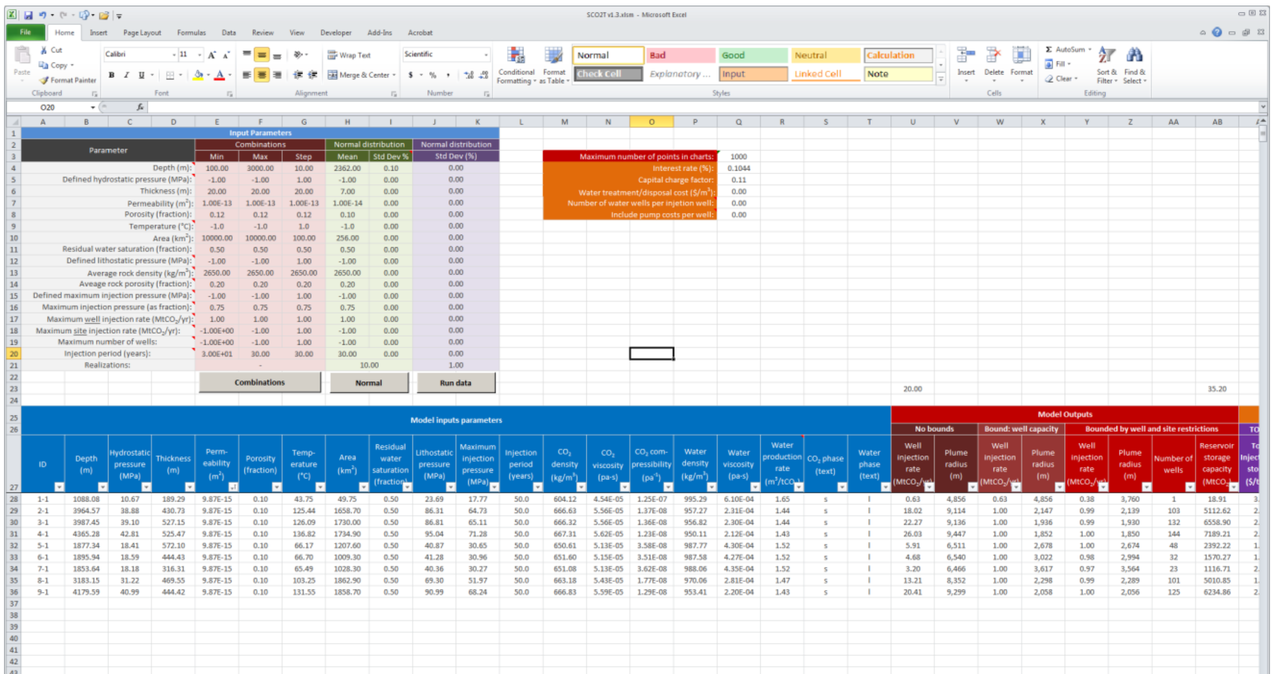
Coupled CO_2 sequestration/EOR systems

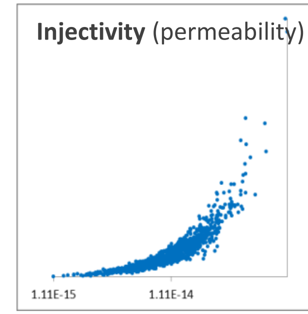


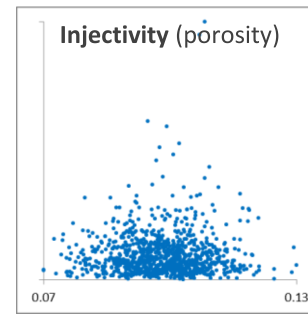
Dai, Middleton, *et al.* (2013) An integrated framework for optimizing CO_2 sequestration and enhanced oil recovery, *Environmental Science & Technology Letters 1*, 49-54.

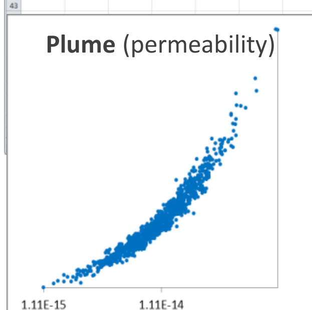
SCO_2T (Sequestration of CO_2 Tool)

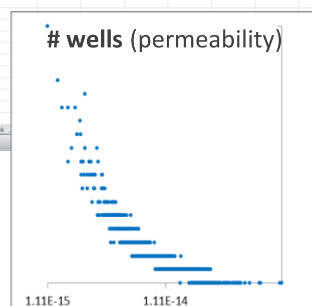
- distributable CO_2 sequestration/EOR framework; VBA+Excel
- present/future: CO_2 fracturing for shale gas

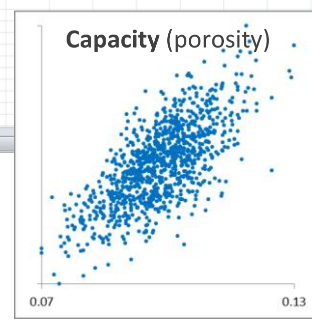


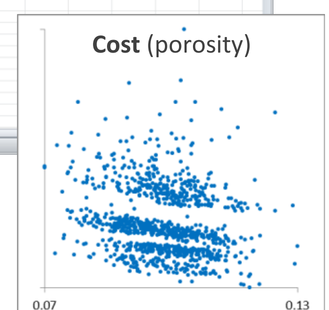










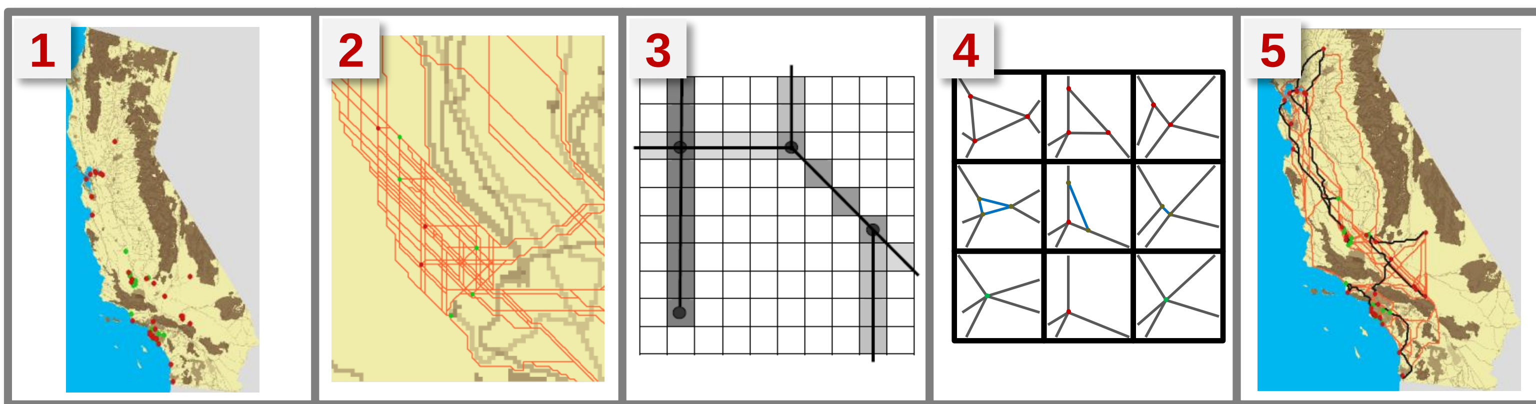


SCO_2T

Candidate Network Generation

Five step process*:

1. Generate construction cost surface
2. Identify potential low-cost paths on cost surface
3. Extract raw candidate *vector* network
4. Refine raw candidate network
5. Network decision model



* **Middleton et al. (2012)** Generating candidate networks for optimization: The CO_2 capture and storage optimization problem, *Computers, Environment and Urban Systems 36*, 18-29.

STEP 1: *Weighted* Cost Surface

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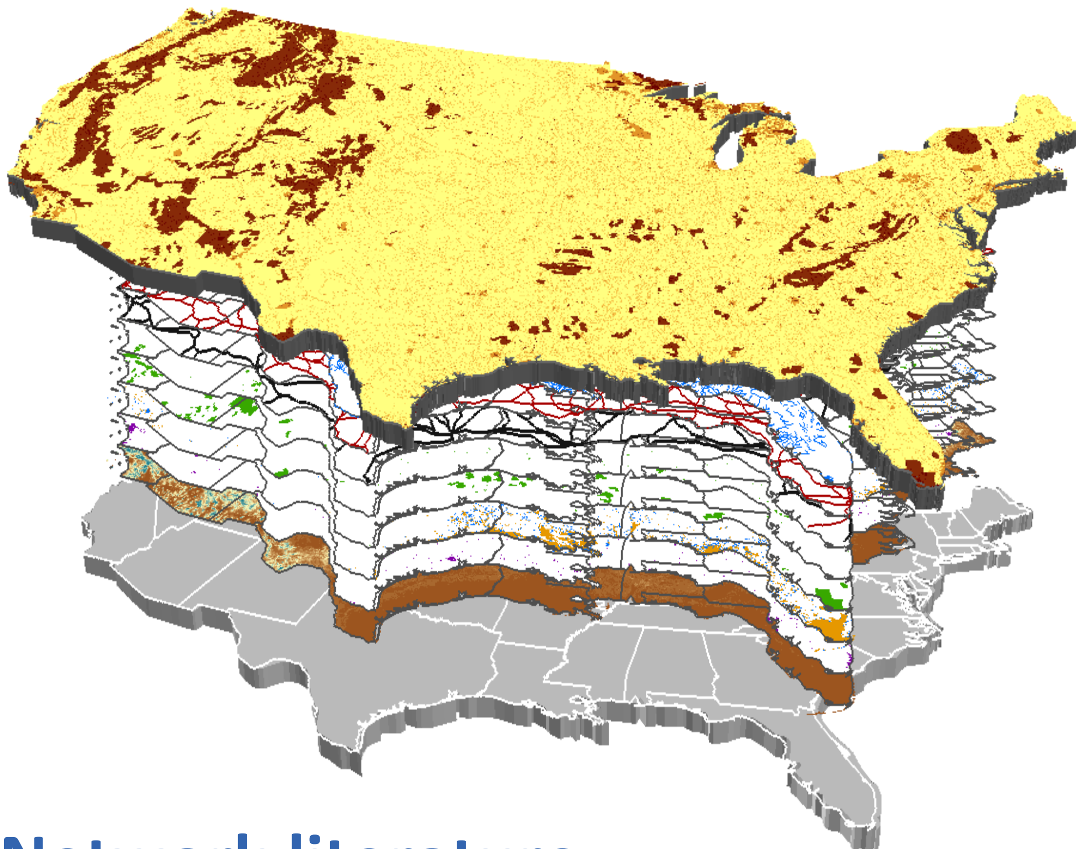


FINAL WEIGHT 1 – 70

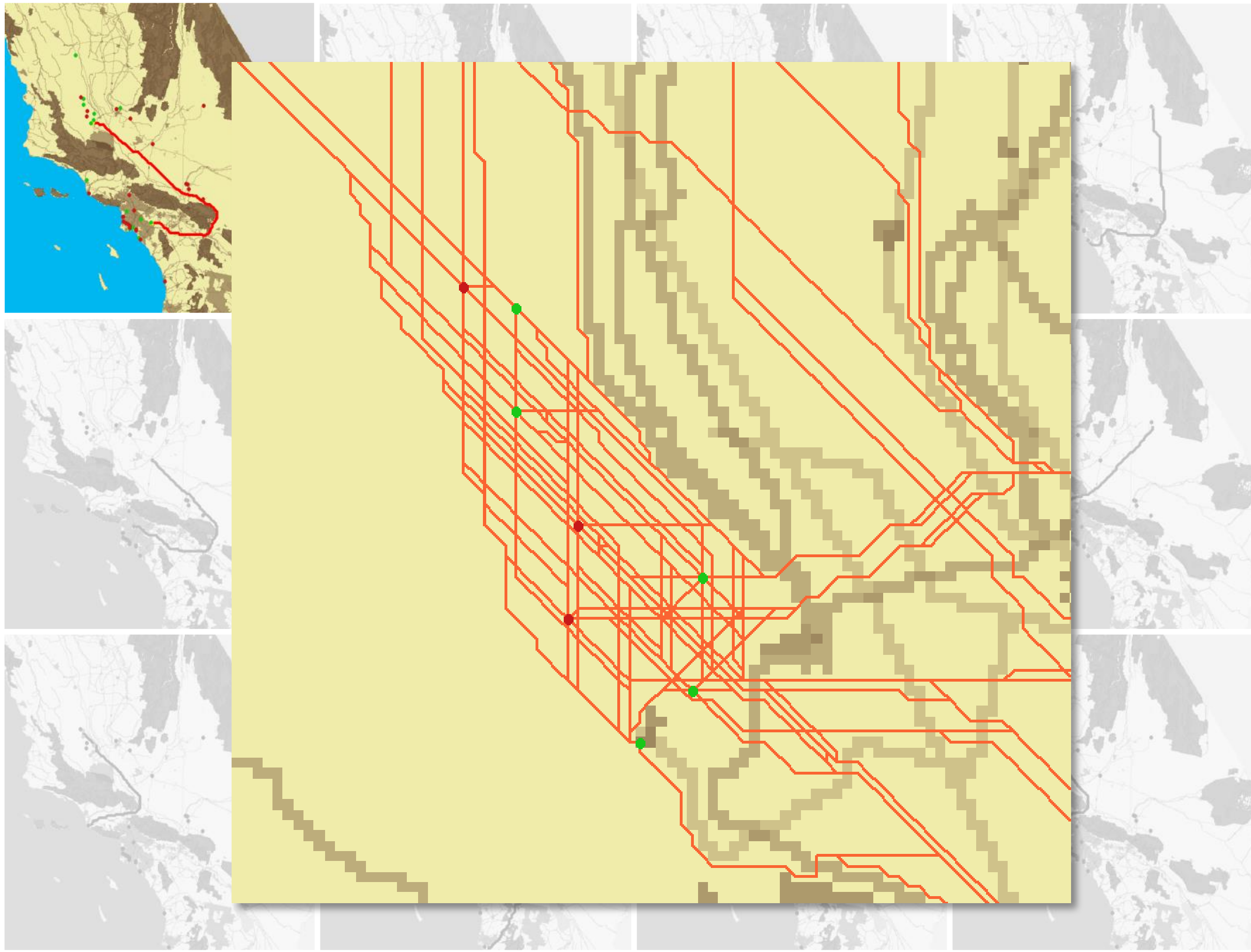
FEATURE	VALUE
Waterways	10
Highway	3
Railroad	3
State Parks	15
National Parks	30
Wetlands	15
Urban	15
Slope	0.1-0.8
Base*	1

*Natural gas pipelines as analog (MIT 2006)

Network literature:

- no quantitative method for generating a candidate network
- expert judgment
- no retrospective analysis

STEP 2: Low Cost *Raster* Paths



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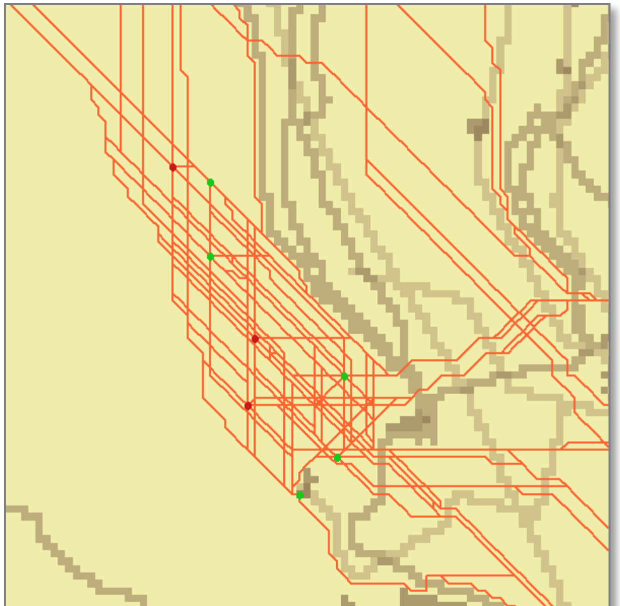
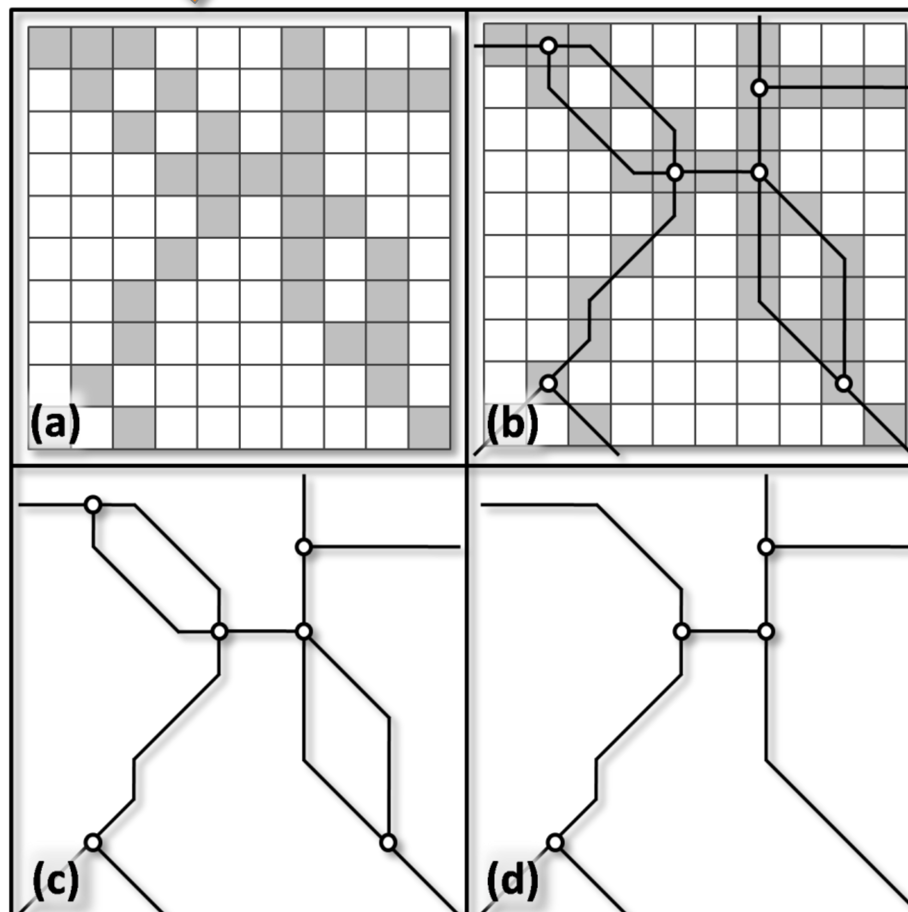
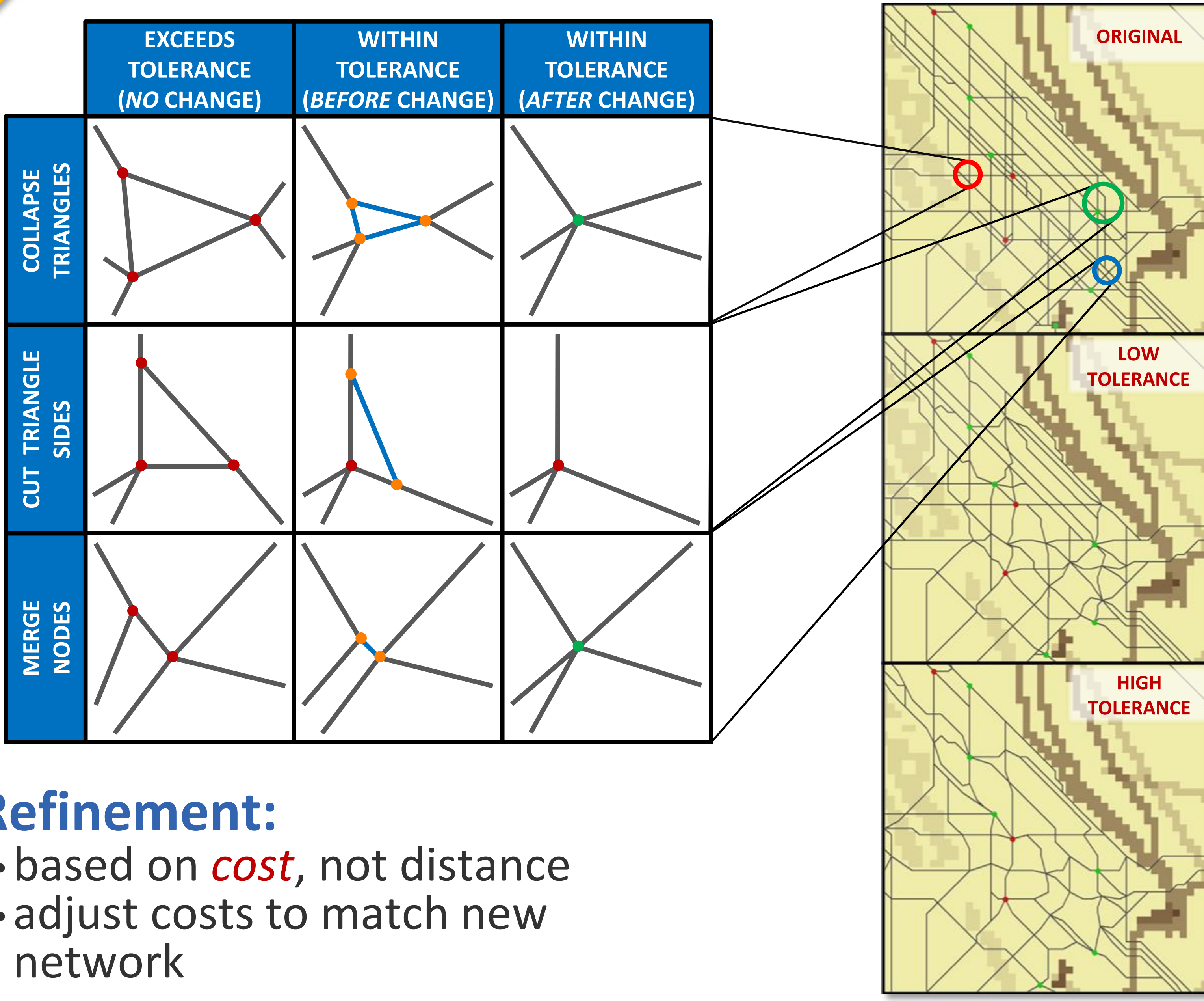
STEP 3: Vector Network Extraction





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

STEP 4: *Raw* Network Refinement



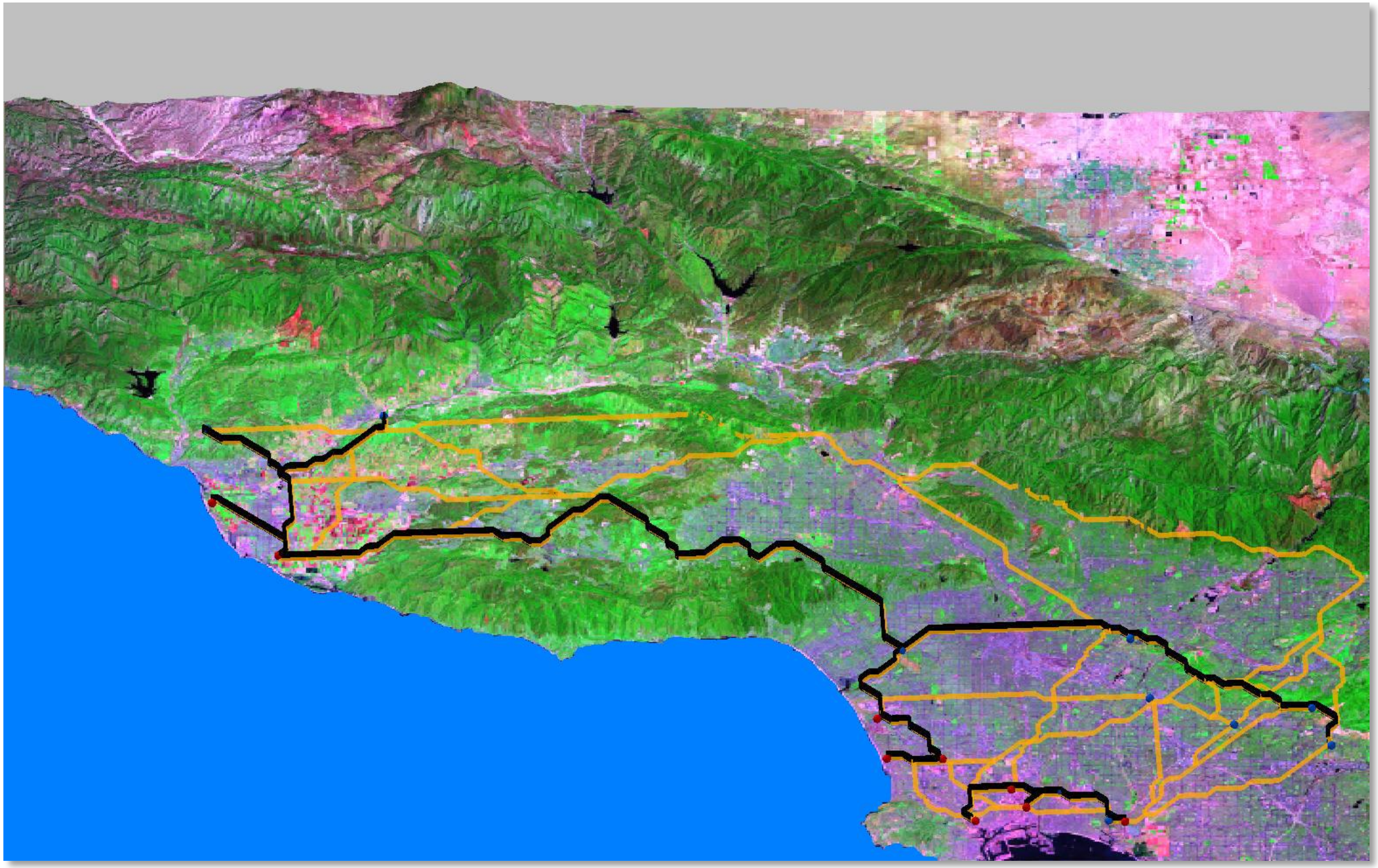
Refinement:

- based on *cost*, not distance
- adjust costs to match new network

STEP 5: Network Decision Model

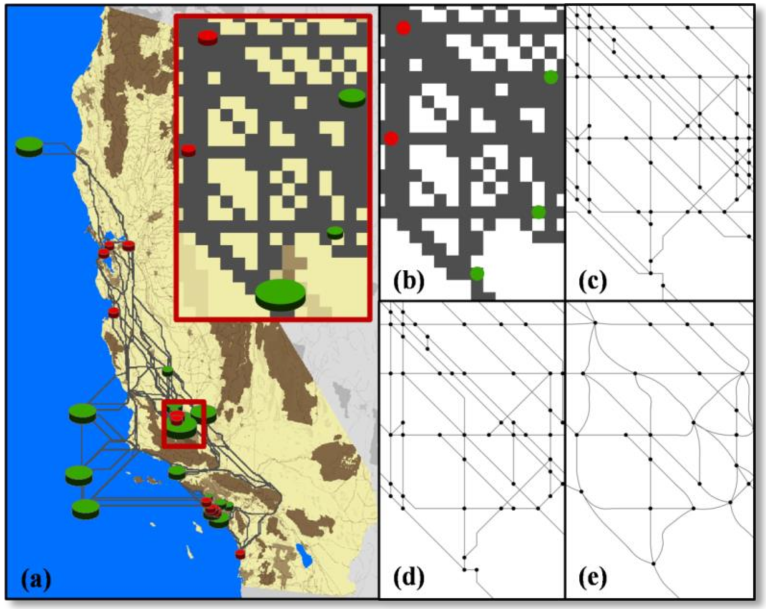
SimCCS:

- Los Angeles basin example



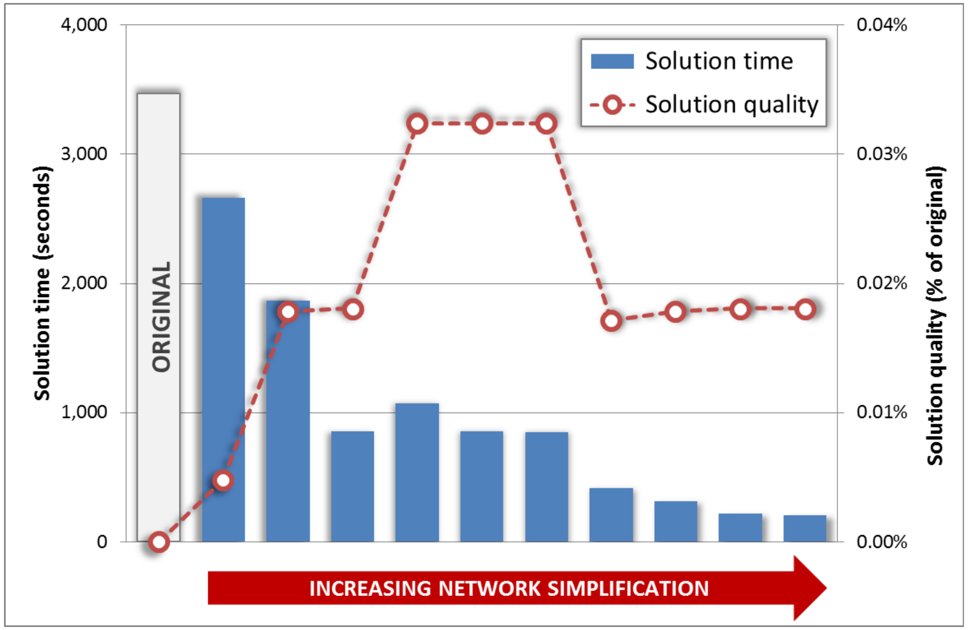
Candidate Network

	Nodes	Arcs	Variables	Constraints
Step 1	793,861	6,354,192	69,896,209	13,502,287
Step 2	14,923	30,716	337,973	76,397
Step 3	1,208	548	6,125	2,346
Step 4	106	320	3,617	788
Step 5	69	232	2,649	575



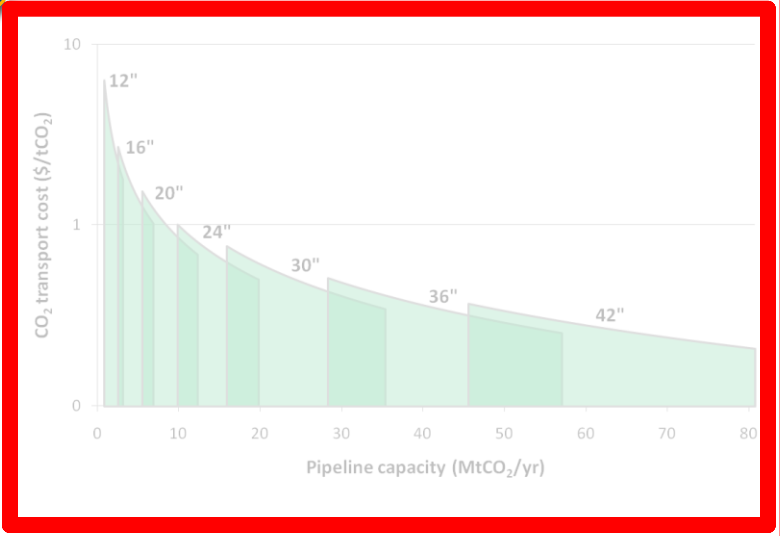
Final candidate network:

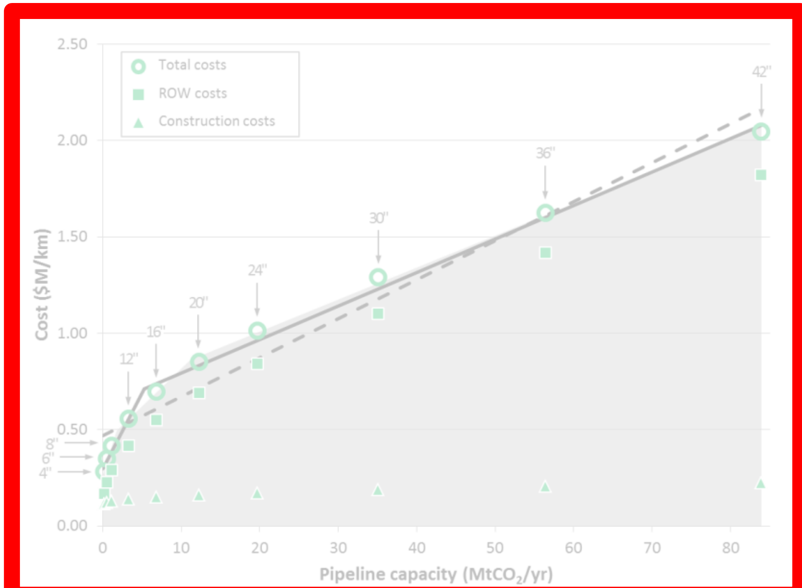
- remove superfluous arcs/nodes
- intractable problems → solvable
- larger and more complex models
- multiple runs: explore uncertainty and sensitivity

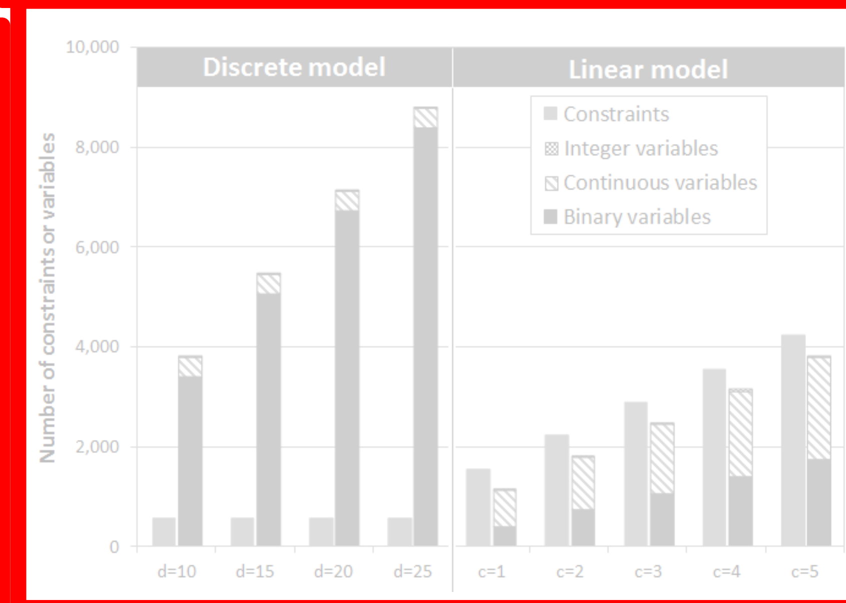


* **Middleton et al. (2012)** Generating candidate networks for optimization: The CO_2 capture & storage optimization problem, *Computers, Environment and Urban Systems 36*, 18-29.

Pipelines: precisely wrong vs. approximately right?







* **Middleton (2013)** A new optimization approach to energy network modeling: anthropogenic CO_2 capture coupled with enhanced oil recovery, *International Journal of Energy Research 37*, 1794-1810.

Pipelines: precisely wrong vs. approximately right?

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LINEAR | DISCRETE

Pipeline diameter (inches)	Pipeline capacity ($MtCO_2$/yr)	Actual cost ($M/km)	One piece Estimate ($M/km)	One piece Error (%)	Two pieces Estimate ($M/km)	Two pieces Error (%)	Three pieces Estimate ($M/km)	Three pieces Error (%)
4"	0.19	0.28	0.48	67.63	0.31	10.00	0.29	2.47
6"	0.54	0.35	0.48	37.50	0.34	-2.81	0.34	-3.17
8"	1.13	0.42	0.49	18.14	0.39	-6.81	0.42	1.00
12"	3.25	0.56	0.54	-3.42	0.57	1.74	0.56	-0.01
16"	6.86	0.70	0.61	-12.79	0.76	8.83	0.70	-0.01
20"	12.26	0.85	0.72	-15.52	0.85	0.27	0.89	3.94
24"	19.69	1.02	0.87	-14.35	0.98	-3.37	1.01	-0.73
30"	35.13	1.29	1.18	-8.58	1.24	-3.66	1.26	-2.30
36"	56.46	1.63	1.61	-0.85	1.61	-1.00	1.61	-0.71
42"	83.95	2.05	2.17	5.90	2.08	1.61	2.07	1.04
	Average (mean) error:		-	7.37%	-	0.48%	-	0.15%
	Absolute mean error:		-	18.47%	-	4.01%	-	1.54%

* **Middleton (2013)** A new optimization approach to energy network modeling: anthropogenic CO_2 capture coupled with enhanced oil recovery, *International Journal of Energy Research 37*, 1794-1810.

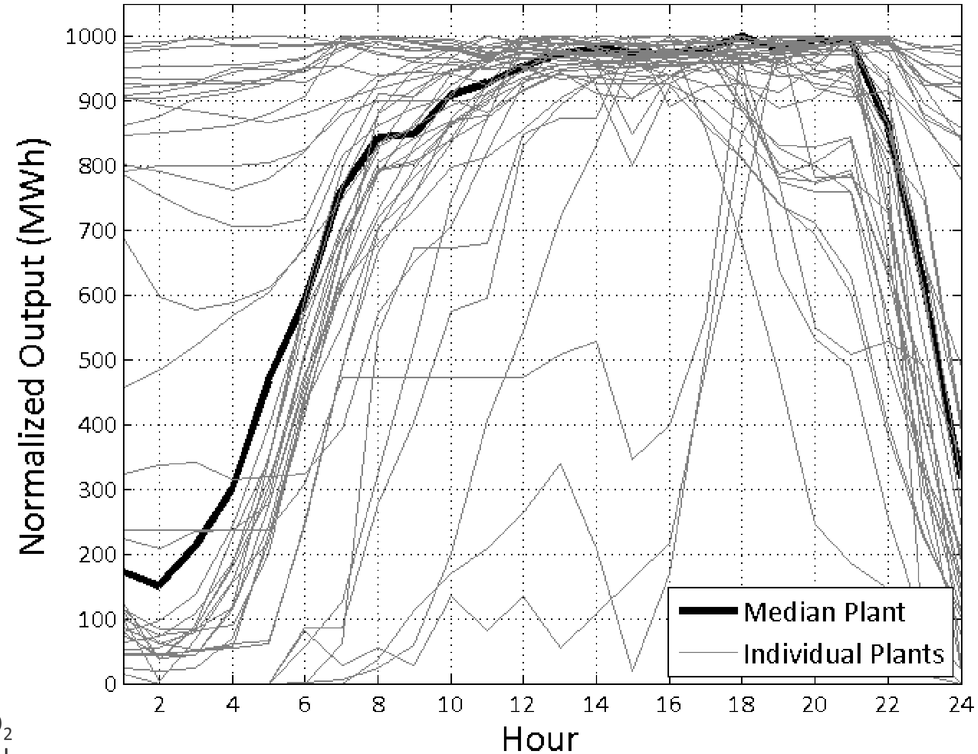
Variable electricity generation

Previous studies

- calculate capture costs assuming generic capacity factor
- includes our own research

New research*

- hourly generation data for 41 natural gas power plants (Ontario, Canada)
- very heterogeneous electricity profiles
- generation normalized in the study



* **Middleton and Eccles (2013)** The complex future of CO_2 capture and storage: Variable electricity generation and fossil fuel power. *Applied Energy* 108, 66-73.

Variable generation and CO_2 capture

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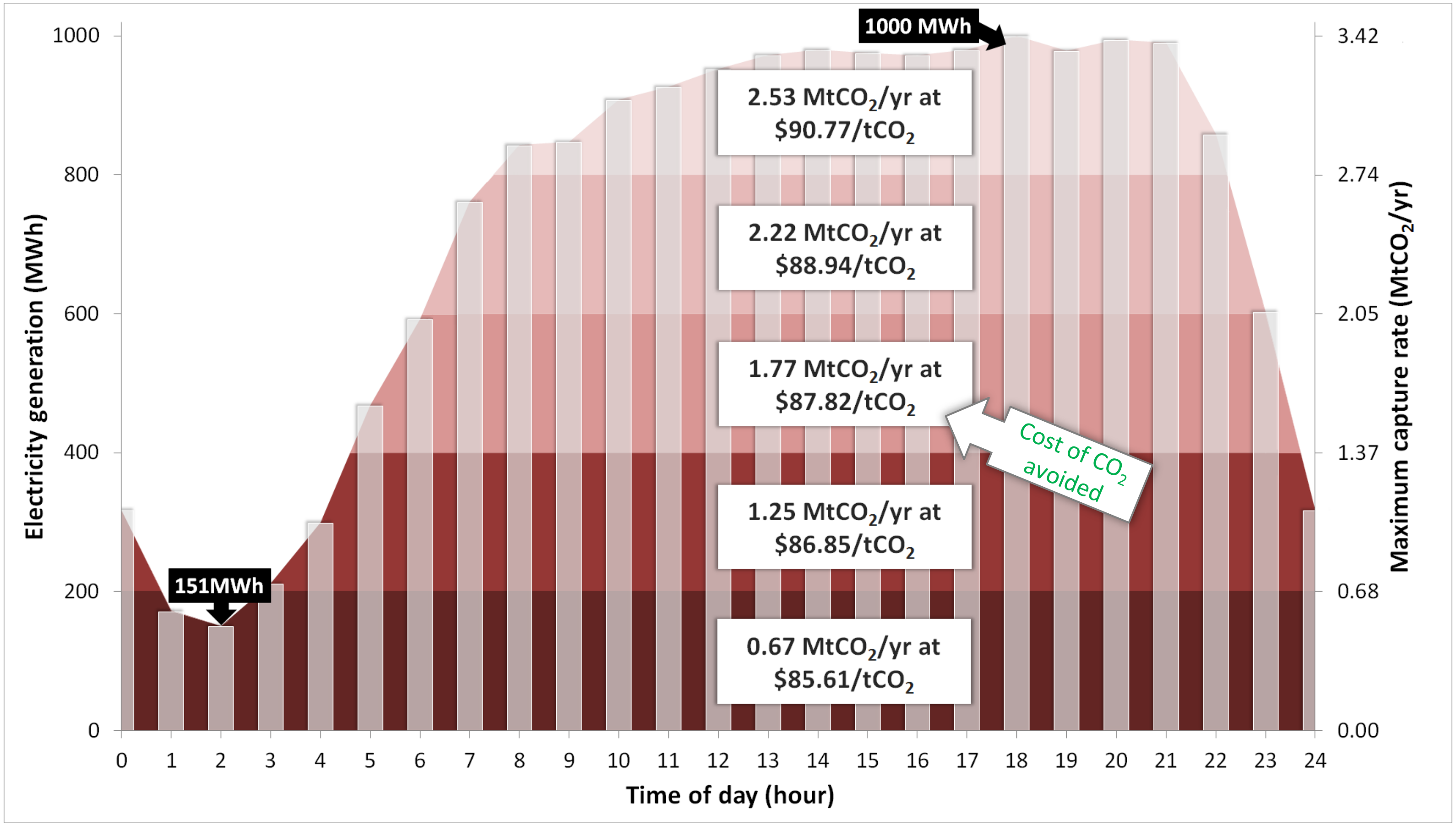
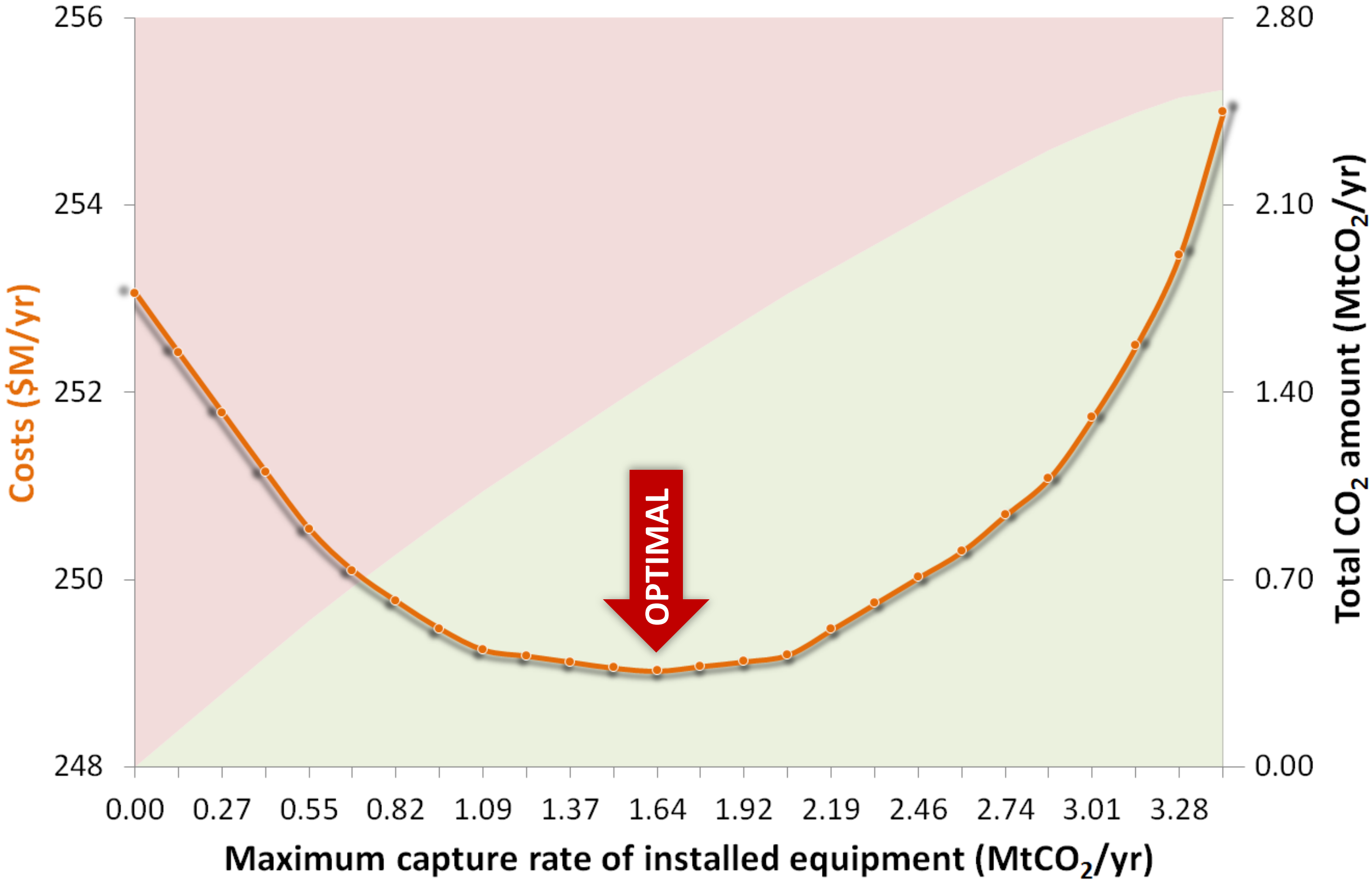
- CO_2 capture profile for the median 1000 MWyr gas plant
- emits 3.8 $MtCO_2$/yr at maximum rate, 90% capture rate
- efficiency of capture equipment changes with capacity
- economic model: includes CO_2 tax and "make-up" electricity



Optimize CO_2 capture infrastructure capacity

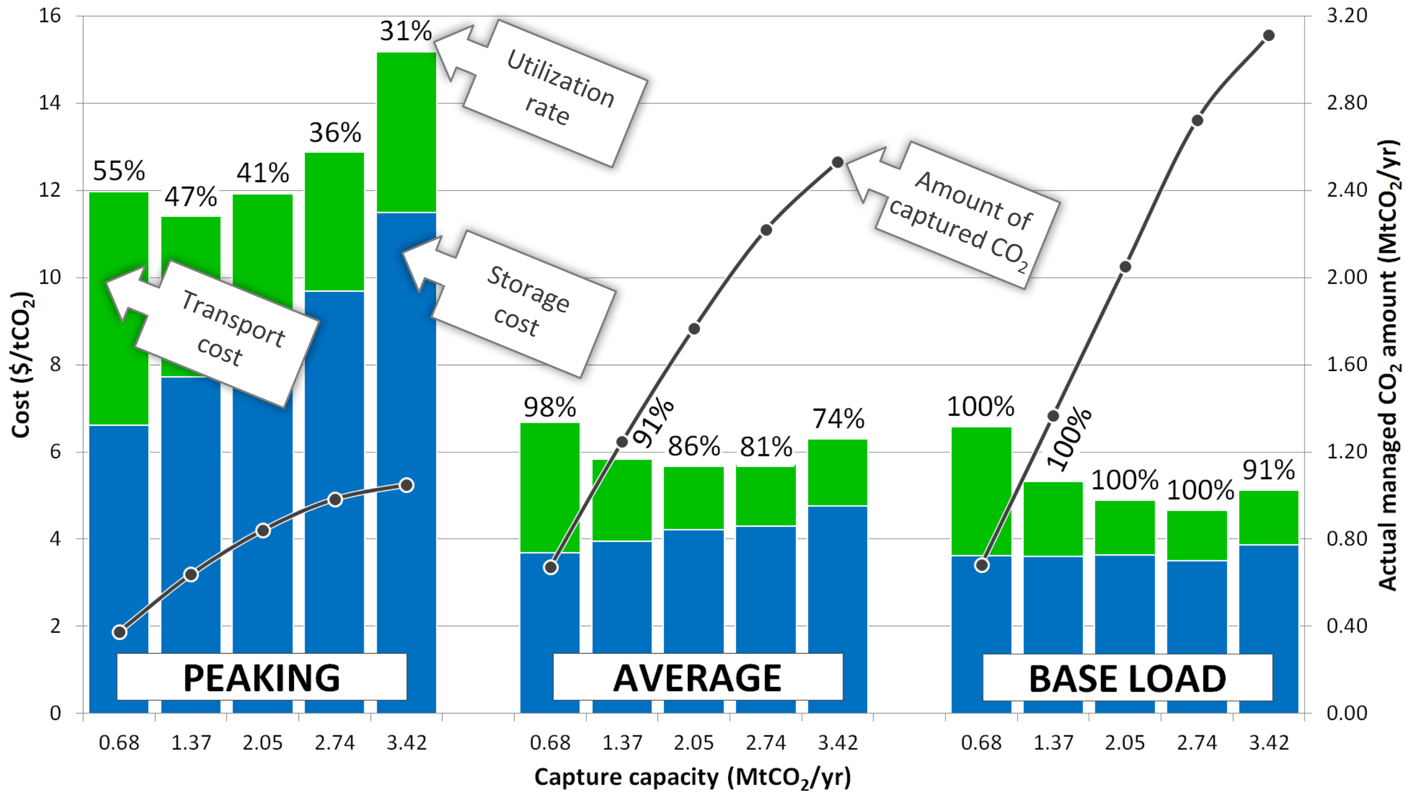
Cost of CO_2 avoided

- (1) fixed, fixed O&M, and variable O&M costs; (2) CO_2 tax; (3) make-up electricity; (4) transport & storage
- optimal: when total annual costs are minimized



Efficiency of transport and storage

- variable electricity = variable CO_2 rate throughout each day
- transport & storage infrastructure utilization rates
- under-utilized infrastructure is much more costly
- onsite temporary storage



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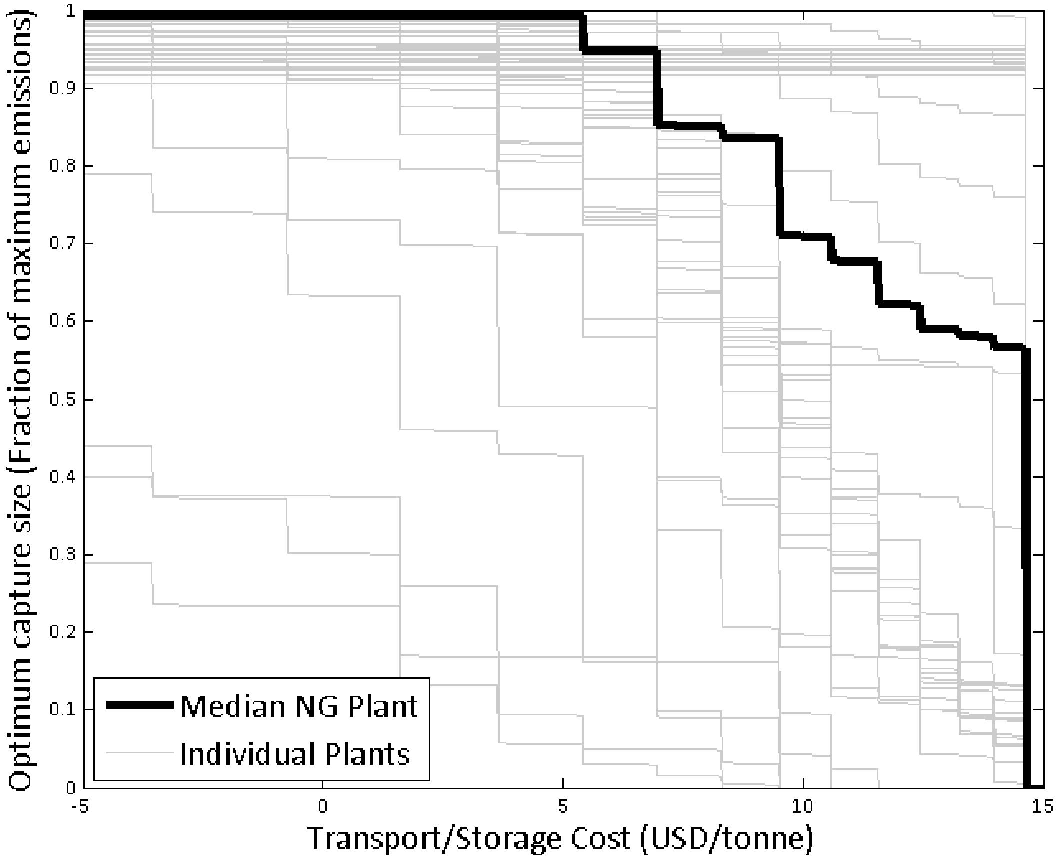
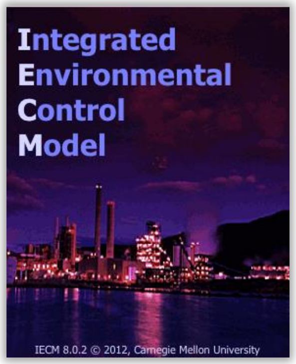
CO_2 transport and storage

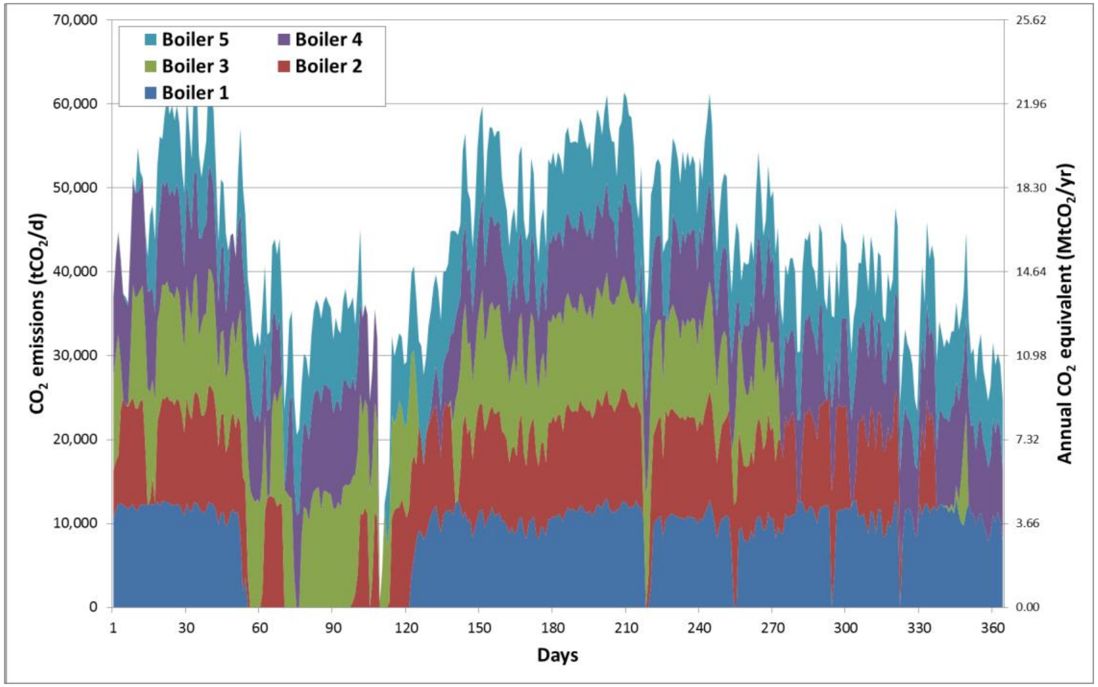
- often considered less important that capture, due to costs
- likely a critical factor for estimating CCS costs and policy
- should be considered endogenously



Economics and engineering

- site-specific data for 1347 boilers (536 plants), including coal type, delivered-coal cost, heat rate, hourly CO_2 and electricity, etc.
- CO_2/electricity from EPA's AMPD
- detailed economic and engineering for 400 coal-fired boilers using IECM





Gibson Generating Station, Indiana (2011)

Geography: delivered coal costs

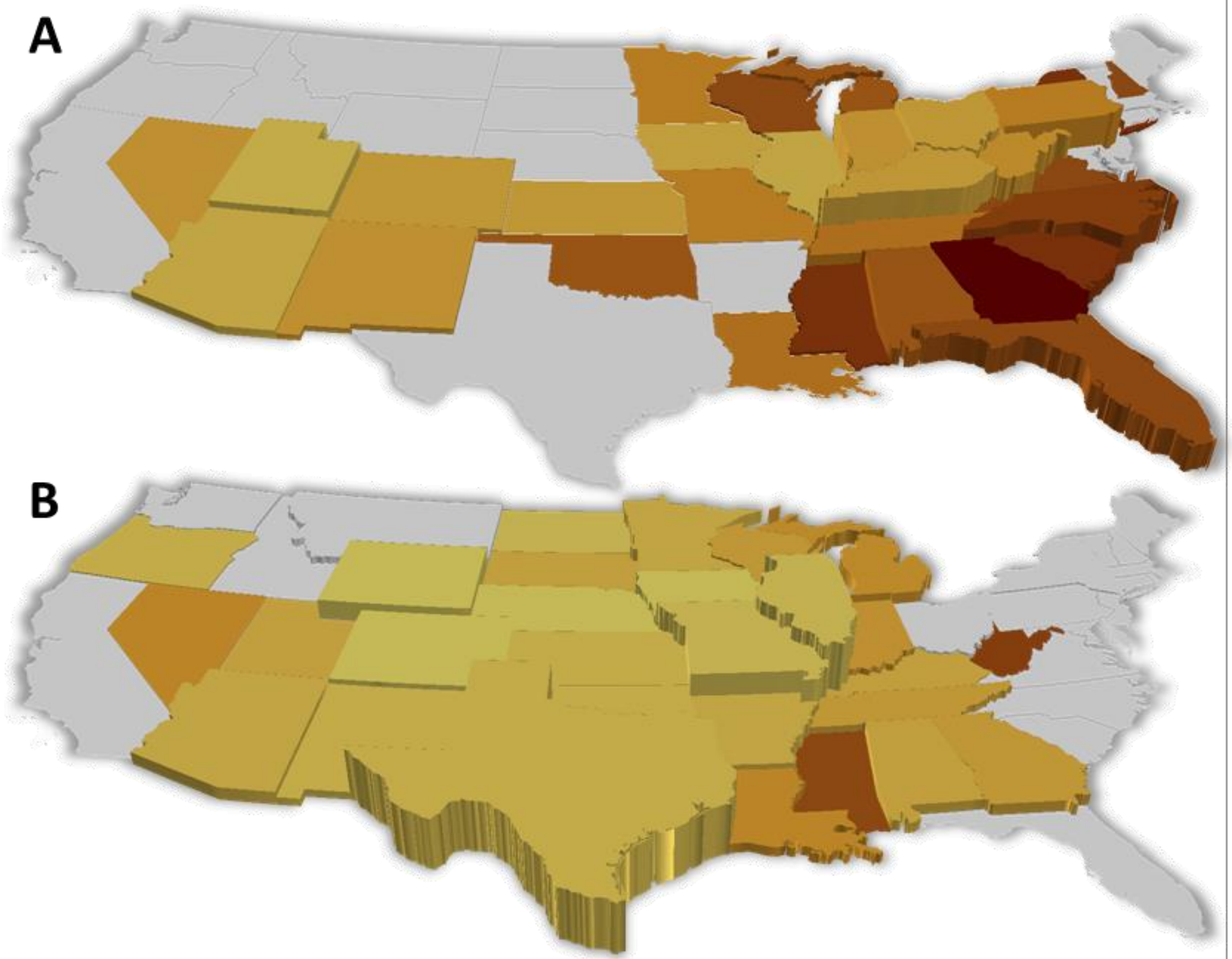


Figure 1: Cost (shading) and total heat(height) of delivered (A) bituminous and (B) sub-bituminous coal. Parts A and B use the same scales. Costs range from \$1.35/GJ (light shading—Iowa) to \$4.34/GJ (dark shading—Georgia). States without sufficient reported costs in Form EIA923 are not shaded. Amount of delivered heat ranges from 0 TJ (no extrusion) to 1,134,373 TJ (1.1 million TJ—Illinois).

Impact of CO_2 emissions

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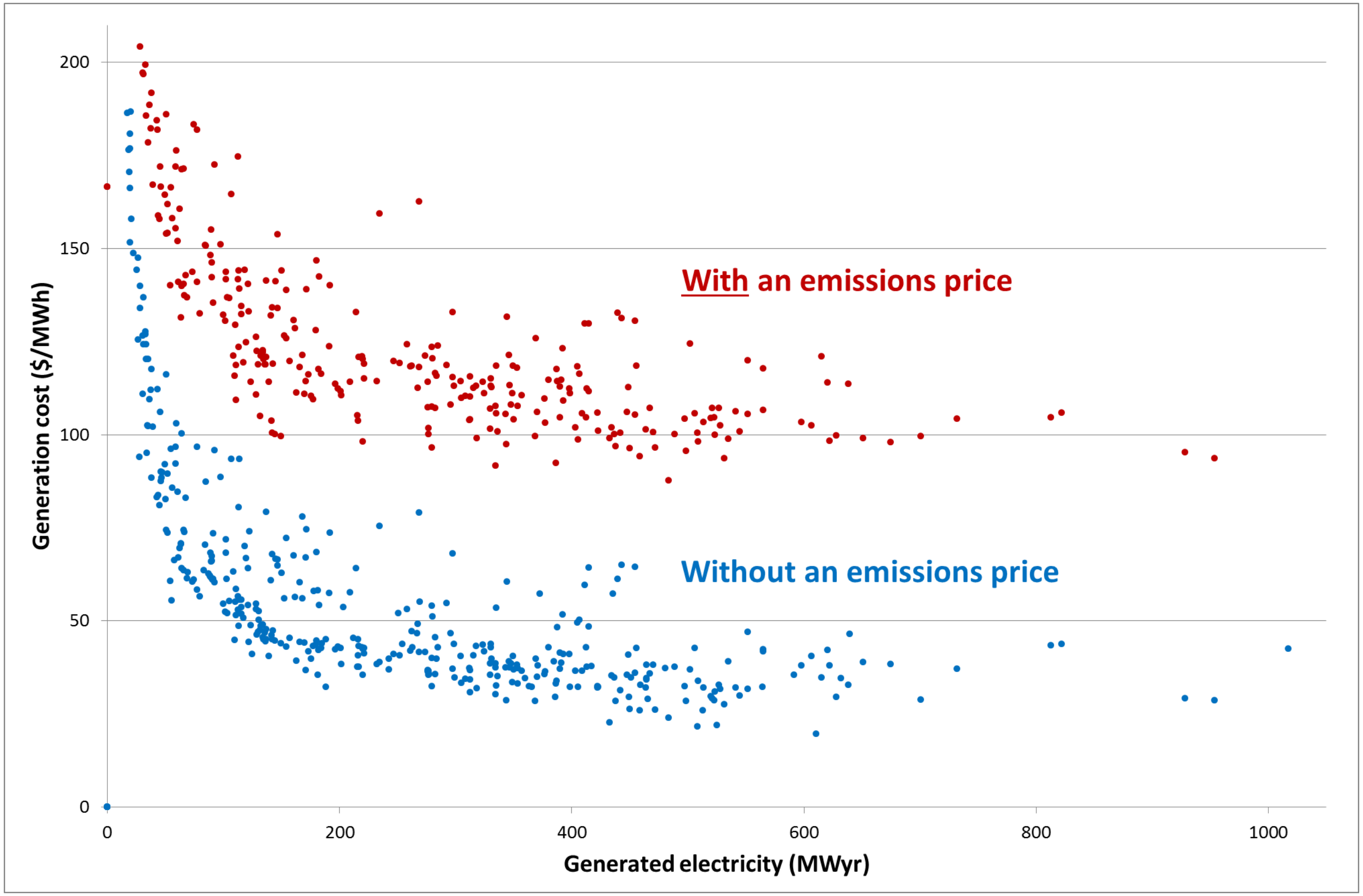
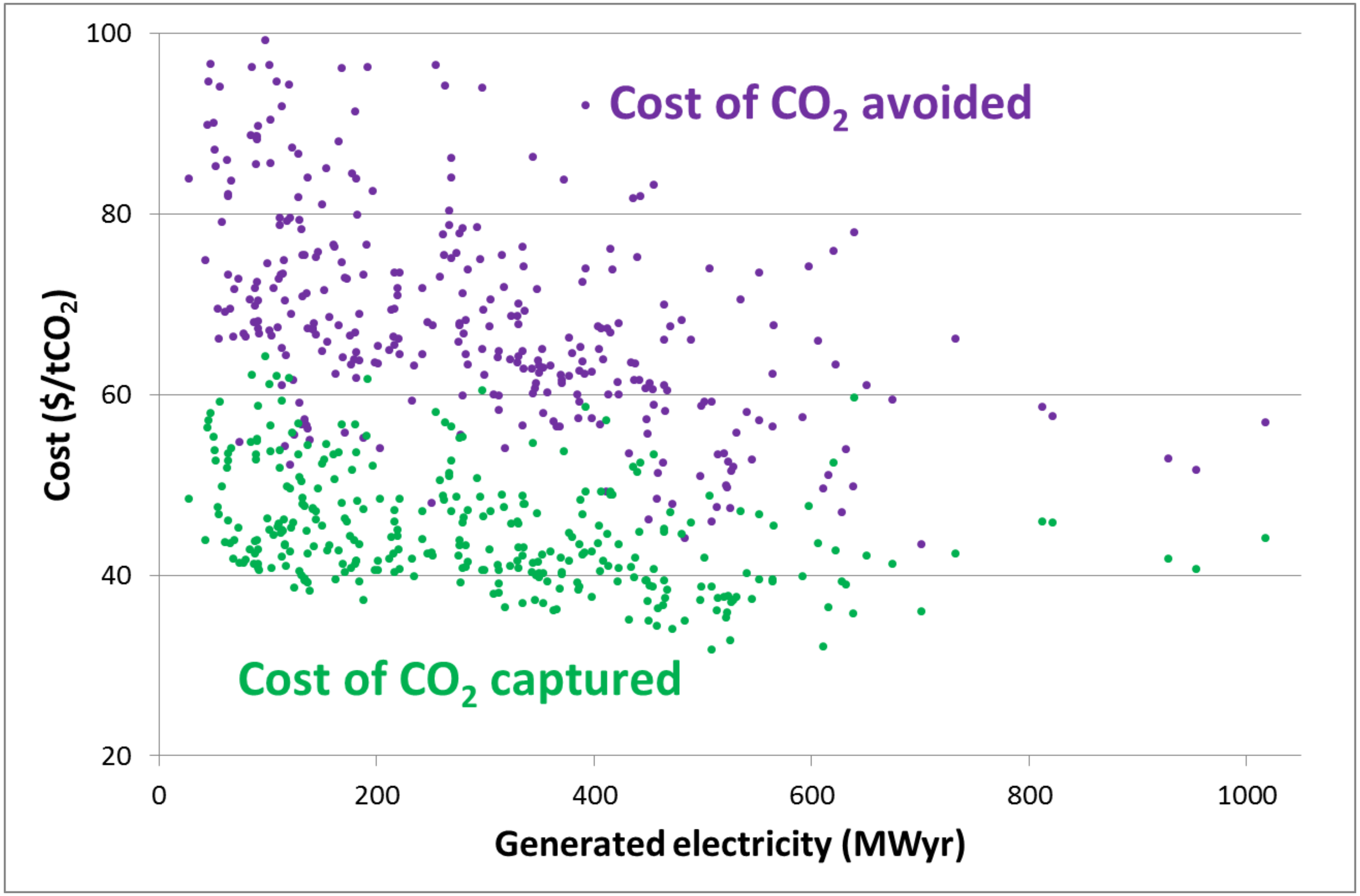
Comparison: post-retrofit electricity costs should be compared to pre-retrofit cist WITH CO_2 emissions price

Chart: CO_2 tax = \$75/tCO_2



CO_2 capture and avoided costs

- CO_2 emissions price = \$100/tCO_2
- plants that do not capture CO_2 at this price are omitted
- marginal cost of CO_2 avoided dictates capture decision



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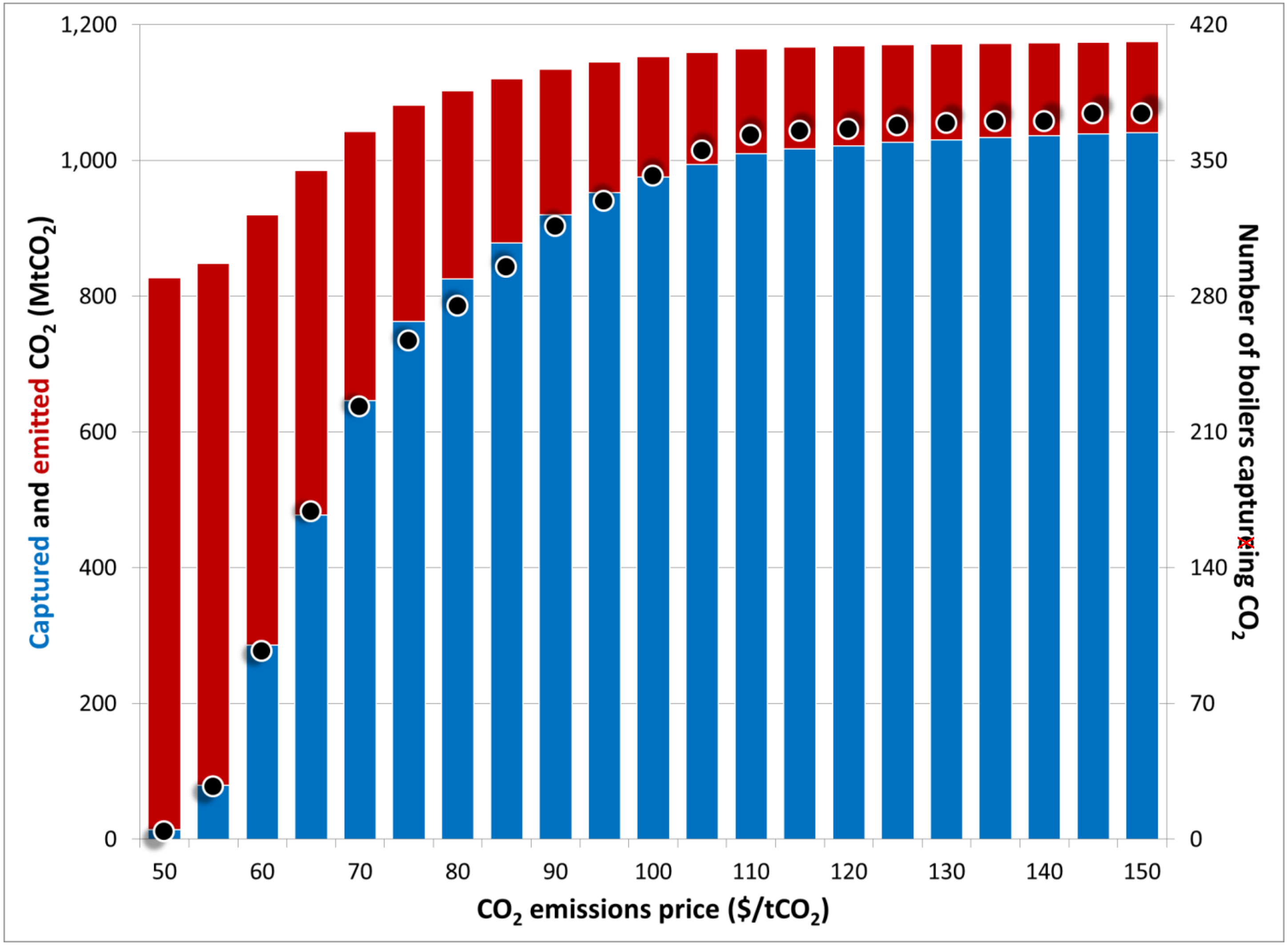
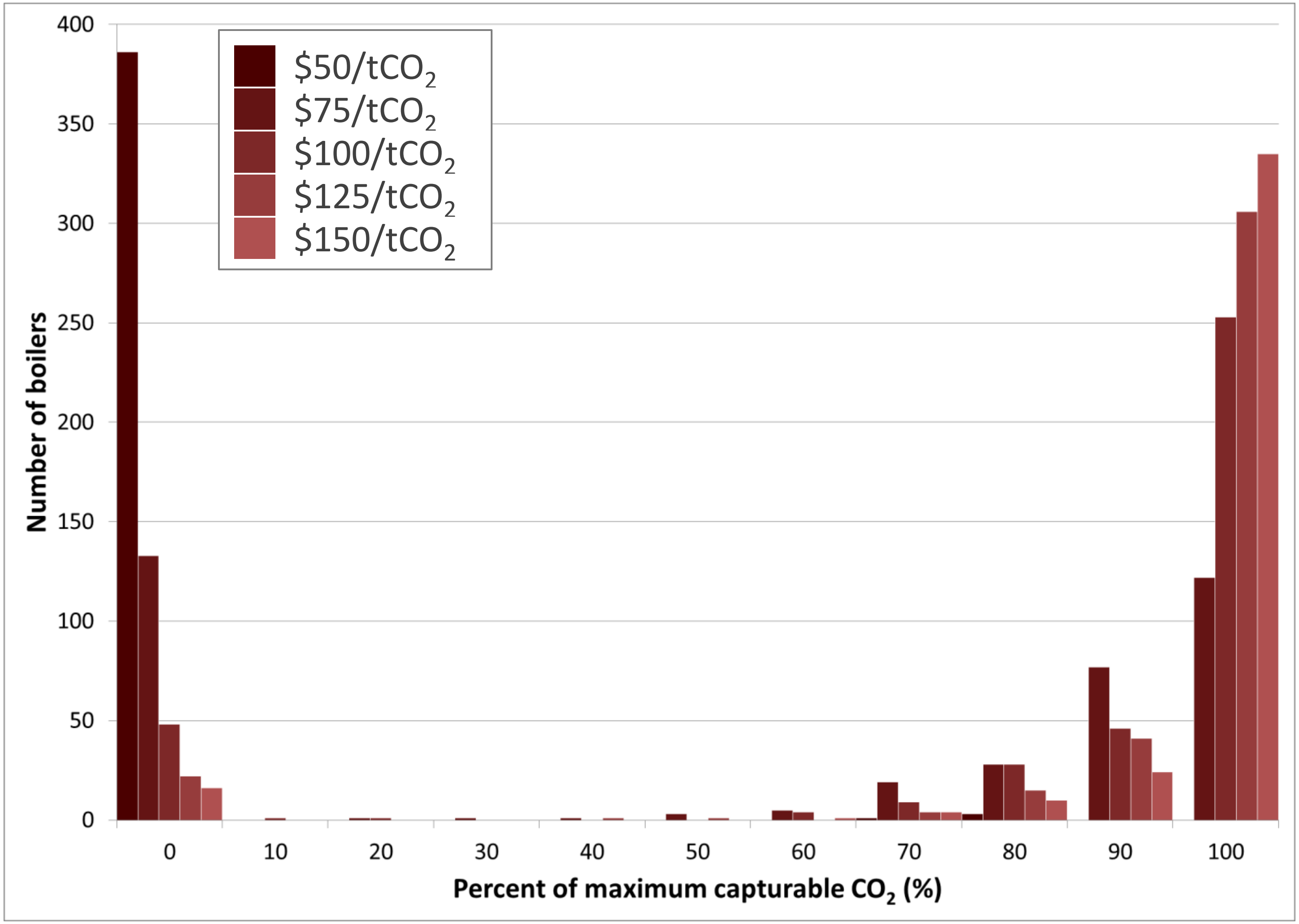
Impact of CO_2 emissions price

- vary emissions price from $50-150/t$CO_2$



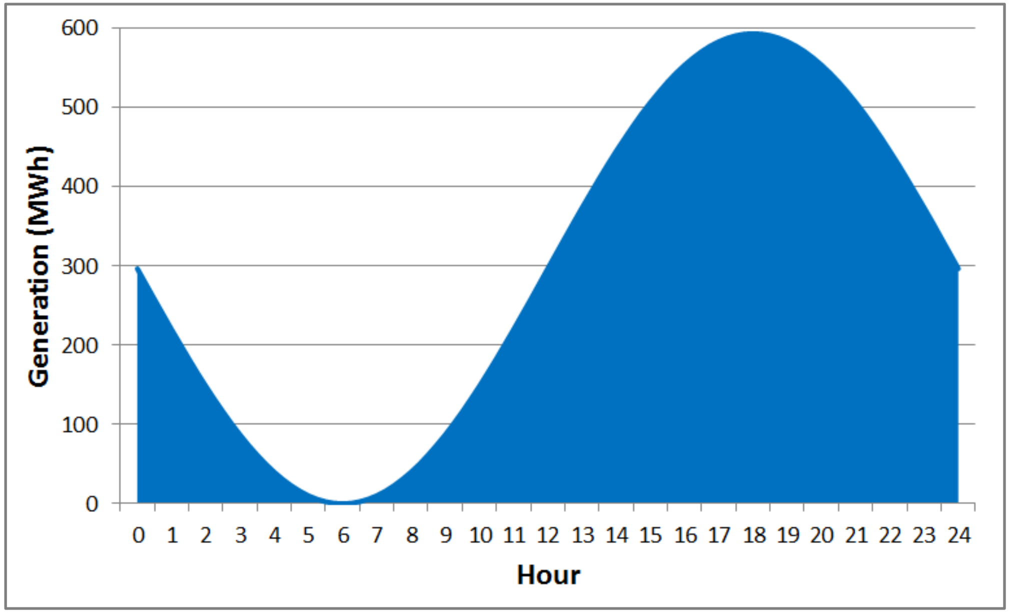
Response to a price on carbon

- tend to capture none or most/all of their capturable CO_2
- relatively small variations in daily profile

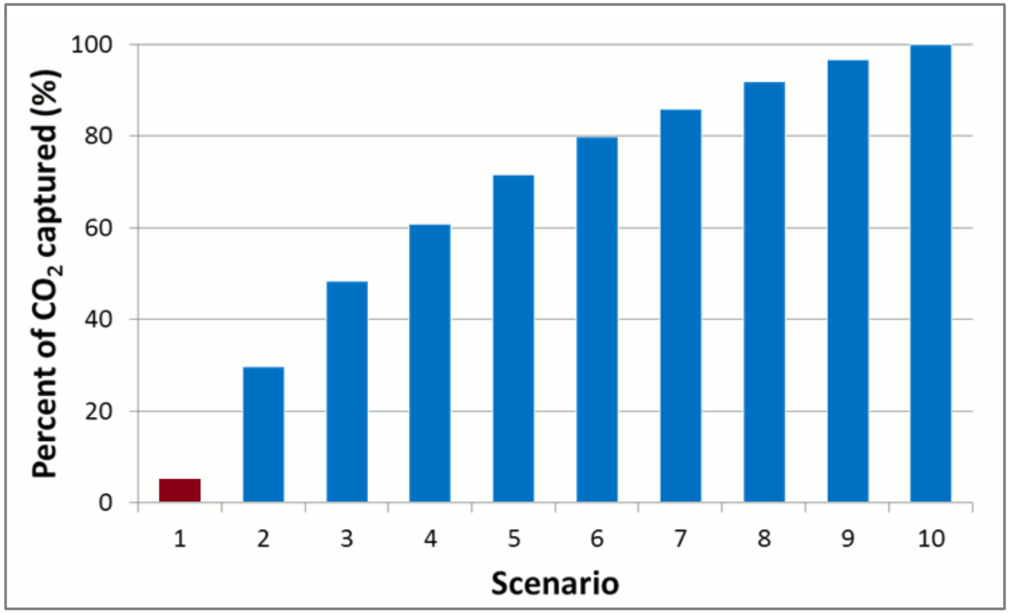


Coal-fired boilers and hourly electricity generation

- ten hypothetical generation profiles
- based on Gibson Generating Station
- simple sine wave



- generation profile drives how much CO_2 the coal-fired plant will capture
- replicates capture performance of natural gas plants



Take home message

CCUS

- significant potential for CO_2 emissions reduction
- requires comprehensive understanding of CO_2 capture-transport-storage/utilization individually and together

Multidisciplinary approach

- combination of engineering (civil/environmental/chemical), economics, policy, decision optimization, etc.

SimCCS

- flexible energy infrastructure approach
- can and has been applied to wind energy, hydrogen economy, biofuels, shale gas, etc.