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# Secure and sustainable energy infrastructure: The case of CO<sub>2</sub> capture, utilization, and storage



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**Richard Middleton**

*Earth and Environmental Sciences  
Los Alamos National Laboratory*

## MENU

### CCS

### What?

### Why?

### Scale?

### SimCCS

### Case studies

### Storage

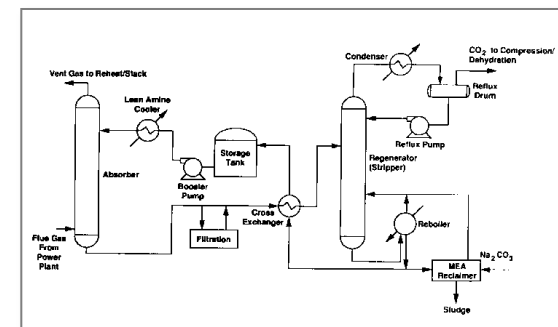
### Transport

### Capture

### La Fin

## (1) Capture

- capture CO<sub>2</sub> at stationary sources (e.g. power plants, cement works, ammonia, oil refineries)
- compress CO<sub>2</sub> to super-critical state



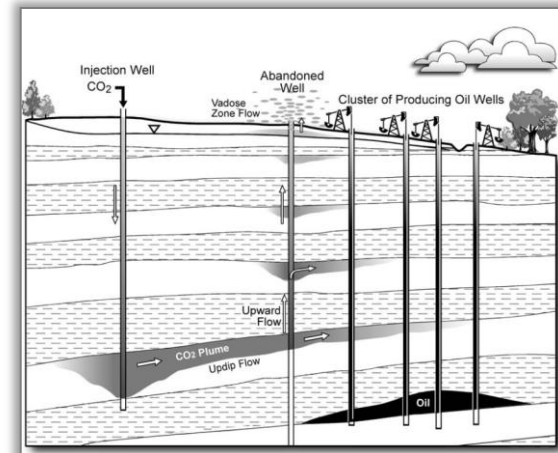
## (2) Transport

- pipelines are the only feasible transport mode
- CO<sub>2</sub> source may be located above geologic reservoir



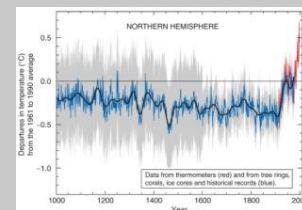
## (3) Utilization and/or Storage

- inject/store CO<sub>2</sub> in geologic reservoirs (e.g. depleted oil fields, deep saline aquifers, unmineable coal seams)
- store/sequester CO<sub>2</sub> for 1,000+ years



## CO<sub>2</sub> Mitigation: *"It's the economy, stupid"...*

CLIMATE



### MENU

CCS

What?

Why?

Scale?

SimCCS

Case studies

Storage

Transport

Capture

La Fin

## Why CCS?

- technology readily available
- 40+ year experience with CO<sub>2</sub> 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<sub>2</sub> footprint of making conventional and non-conventional oil



## MENU

### CCS

What?

Why?

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SimCCS

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Storage

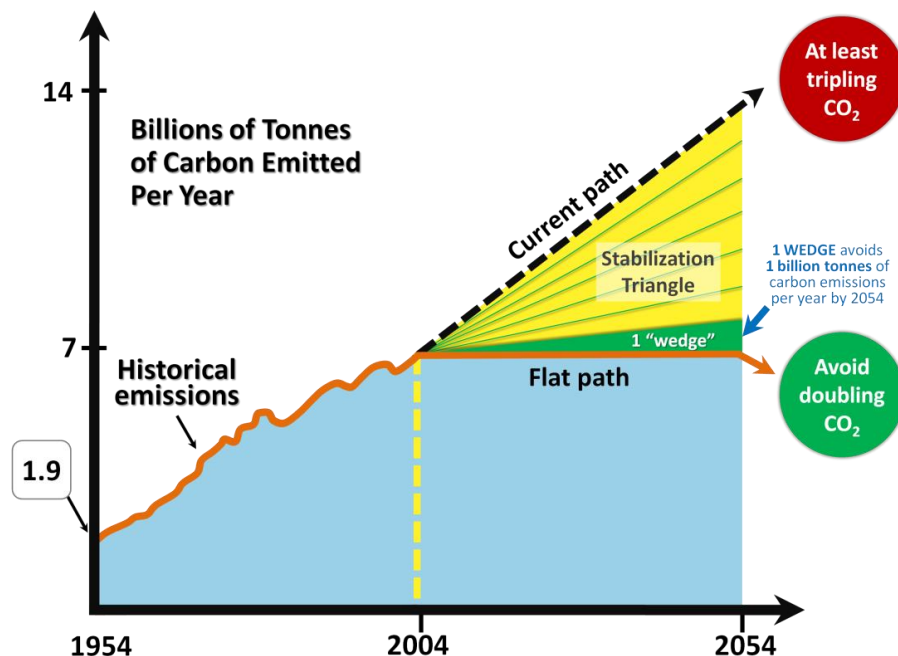
Transport

Capture

La Fin

## Meaningful CCS

- stabilization wedge  
→ abate 1,000 MtC/yr or  
**3,670 MtCO<sub>2</sub>/yr**
- U.S. CCS: **920 MtCO<sub>2</sub>/yr**<sup>1</sup>
- manage **1,164 MtCO<sub>2</sub>/yr**<sup>2</sup>  
coal: 2,150 MtCO<sub>2</sub>/yr<sup>3</sup>
- 245 coal power plants<sup>2,3</sup>



## Comparison:

### CCS INFRASTRUCTURE MODELING IS CRITICAL

(i) where & (ii) how much CO<sub>2</sub> to capture; (iii) where & (iv) how much CO<sub>2</sub> to inject/store; (v) where, (vi) size, & (vii) networking of pipelines; (viii) optimally allocate CO<sub>2</sub>

# 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<sup>CAP</sup>**: cap-and-trade environment
  - SimCCS<sup>PRICE</sup>**: CO<sub>2</sub> tax
  - SimCCS<sup>TIME</sup>**: infrastructure evolution

## OPTIMIZATION ENGINE

$$\sum_{i \in S} \text{Cost to open source, capture CO}_2 (a_i) + \sum_{i \in I, j \in N_i, d \in D} \text{Cost to purchase land, construct pipeline, and transport CO}_2 (\sum_{j \in N_i} x_{ij} y_{ijd}) + \sum_{j \in R} \text{Cost to open reservoir, inject CO}_2 (b_j)$$

$$(1) \quad x_{ij} - \sum_{d \in D} \max Q_{ijd}^p y_{ijd} \leq 0 \quad \forall i \in I, j \in N_i$$

CO<sub>2</sub> flow must be less than maximum pipeline capacity

$$(2) \quad x_{ij} - \sum_{d \in D} \min Q_{ijd}^p y_{ijd} \geq 0 \quad \forall i \in I, j \in N_i$$

CO<sub>2</sub> flow must be more than minimum pipeline capacity

$$(3) \quad \sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0 \quad \forall i \in I$$

CO<sub>2</sub> flow leaving a node must equal inflow

$$(4) \quad a_i - Q_i^s s_i \leq 0 \quad \forall i \in S$$

CO<sub>2</sub> captured at a source must not exceed supply

$$(5) \quad b_j - Q_j^r r_j \leq 0 \quad \forall j \in R$$

CO<sub>2</sub> stored at a sink must not exceed capacity

$$(6) \quad \sum_{i \in S} a_i \geq T$$

Target amount of CO<sub>2</sub> to store or sequester

$$(7) \quad \sum_{d \in D} y_{ijd} \leq 1 \quad \forall i \in I, j \in N_i$$

Only one pipeline can be built between nodes

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

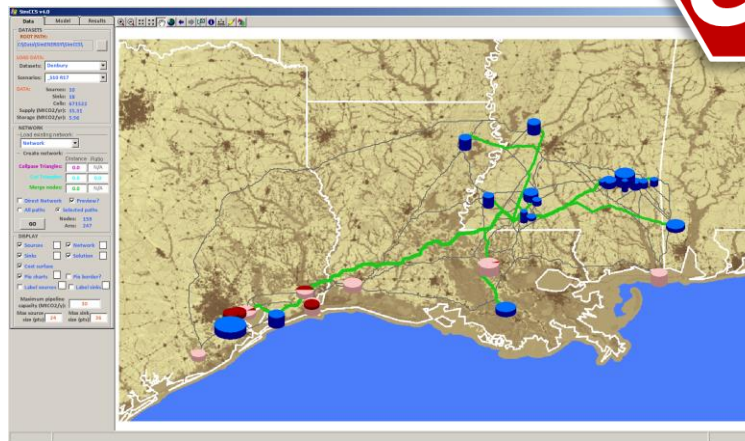
0,1 constraints

$$x_{ij} \geq 0 \quad \forall i, j \in N_i$$

Non-negativity constraints

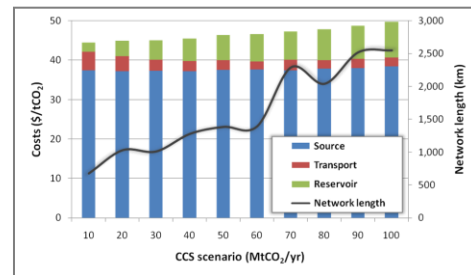
## INTERFACE

## POLICY ANALYSIS



Spatial analysis

Economics & engineering



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

# SimCCS: Scalable Infrastructure Model for CCS

## MENU

CCS

SimCCS

Overview

Framework

MILP

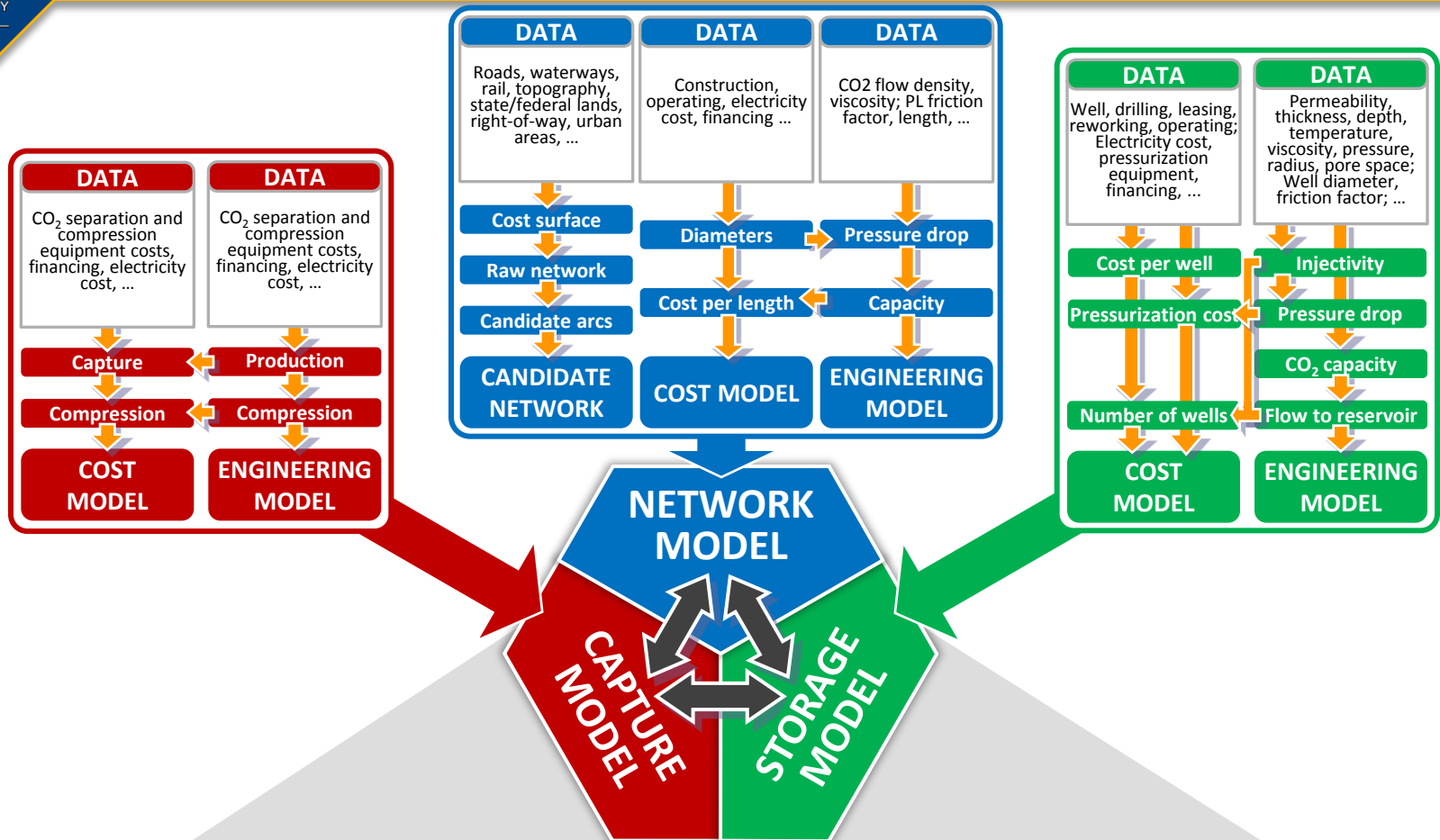
Case studies

Storage

Transport

Capture

La Fin



COSTS	SPATIAL DEPLOYMENT	CO <sub>2</sub> FLOWS	GENERAL
Cost to deploy CCS infrastructure	Where to capture and/or release CO <sub>2</sub>	CO <sub>2</sub> amount to be captured at each source	Amount of CO <sub>2</sub> cost-effectively sequestered
Capture, transport, and storage costs	Location of capture-ready CO <sub>2</sub> sources	How much CO <sub>2</sub> should be stored in each reservoir	Scale of CCS infrastructure
Carbon tax (\$/tonne)	Which reservoirs should inject/store CO <sub>2</sub>	CO <sub>2</sub> pipeline capacities	Policy implications
Cap and trade pricing	Dedicated CO <sub>2</sub> pipeline network	CO <sub>2</sub> allocation between sources and reservoirs	Tradeoff between capture, transport, and storage

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

Costs: Capture, transport, storage, and tax

Subject to:

$$x_{ij} \leq \sum_{c \in C} p_{ijc} \quad \forall i \in I, \forall j \in N_i \tag{2}$$

CO<sub>2</sub> flow

$$Q_c^p y_{ijc} \leq p_{ijc} \leq Q_c^{p'} y_{ijc} \quad \forall i \in I, \forall j \in N_i, \forall c \in C \tag{3}$$

Pipeline capacity

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

CO<sub>2</sub> mass balance

$$a_i \leq Q_i^s s_i \quad \forall i \in S, \forall g \in G_i \tag{5}$$

CO<sub>2</sub> capture

$$b_j \leq Q_j^w w_j \quad \forall j \in R \tag{6}$$

CO<sub>2</sub> storage

$$w_j \leq P_j^w r_j \quad \forall j \in R \tag{7}$$

Injection wells

$$y_{ijc} \in \{0,1\} \quad \forall i \in I, \forall j \in N_i, \forall d \in D \tag{8}$$

Variable

$$s_i \in \{0,1\} \quad \forall i \in S, \forall g \in G_i \tag{-}$$

definitions

$$r_j \in \{0,1\} \quad \forall j \in R \tag{-}$$

and bounds

$$w_j \in \{0,1,2, \dots, n\} \quad \forall j \in R \tag{-}$$

$$x_{ij} \geq 0 \quad \forall i \in I, \forall j \in N_i \tag{-}$$

$$a_i \geq 0 \quad \forall i \in I \tag{-}$$

$$b_j \geq 0 \quad \forall j \in R \tag{-}$$



## MENU

CCS

SimCCS

Case studies

SoCo

Ordos Basin

Oil sands

Dynamicism

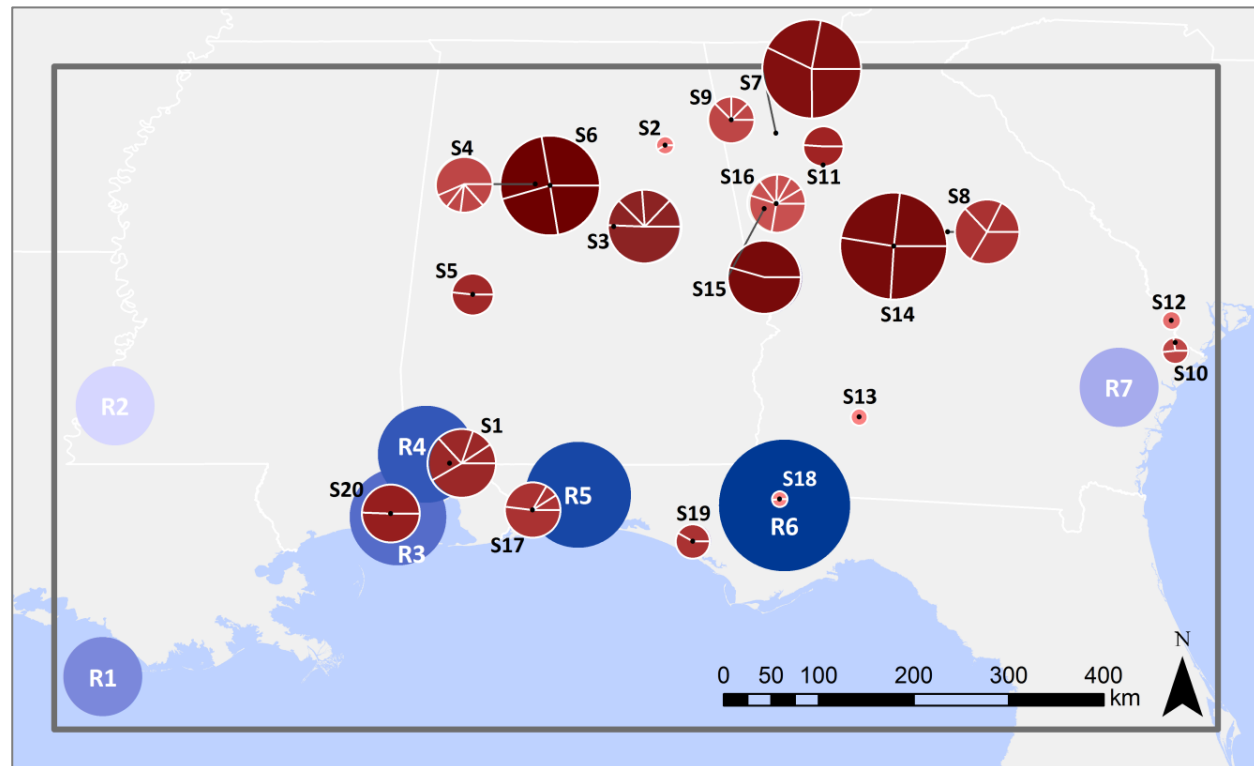
Storage

Transport

Capture

La Fin

- 10 year business plan and CO<sub>2</sub> emissions strategy
- 20 coal-fired plants, **156 MtCO<sub>2</sub>/yr** emissions
- 65 individual boilers → boiler level accuracy
- capture costs: **\$46-102/tCO<sub>2</sub>** (plant) & **\$41-166/tCO<sub>2</sub>** (boiler)
- storage: 3.4 GtCO<sub>2</sub> in 7 sinks, **113 MtCO<sub>2</sub>/yr** over 30 years
- storage costs: **\$3.78-8.60/tCO<sub>2</sub>**





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**SoCo**

Ordos Basin

Oil sands

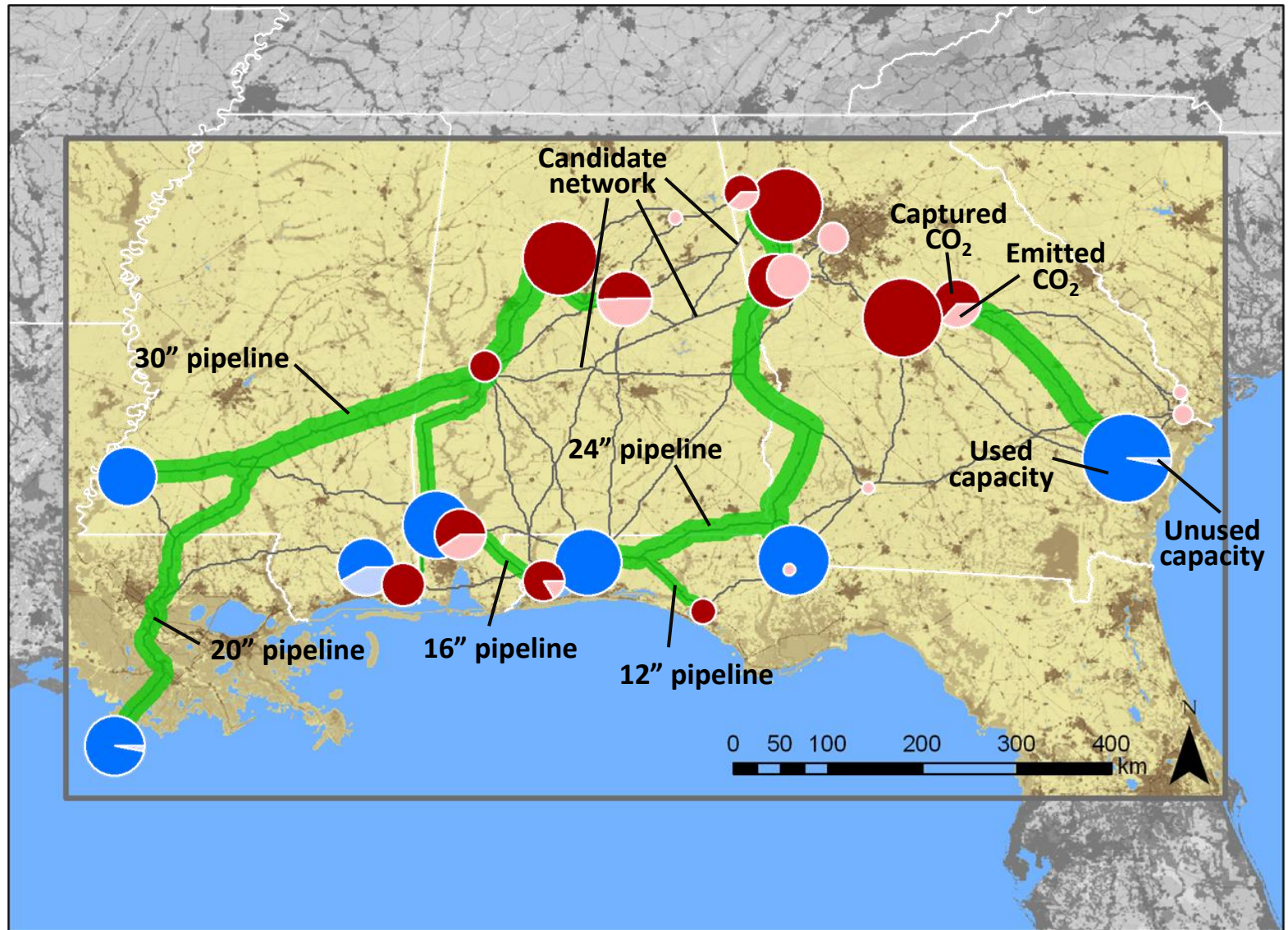
Dynamicism

Storage

Transport

Capture

La Fin



\* Middleton et al. (2012) The cross-scale science of CO<sub>2</sub> capture and storage: from pore scale to regional scale, *Energy & Environmental Science* 5, 7328-7345.

# SoCo: 5 to 110 MtCO<sub>2</sub>/yr scenarios

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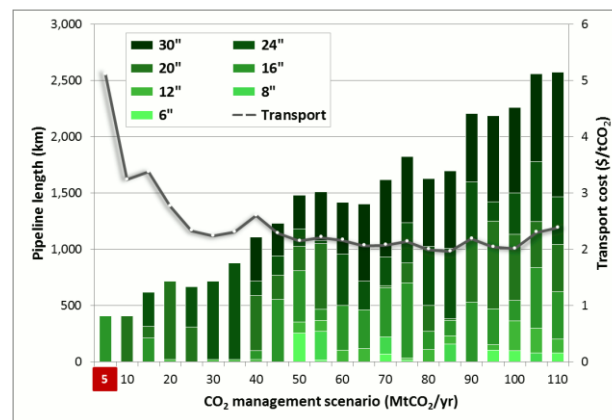
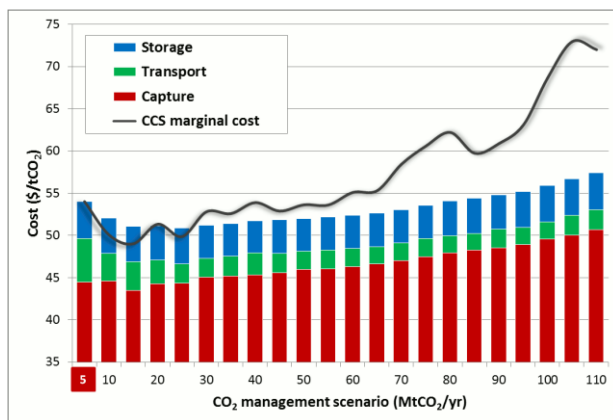
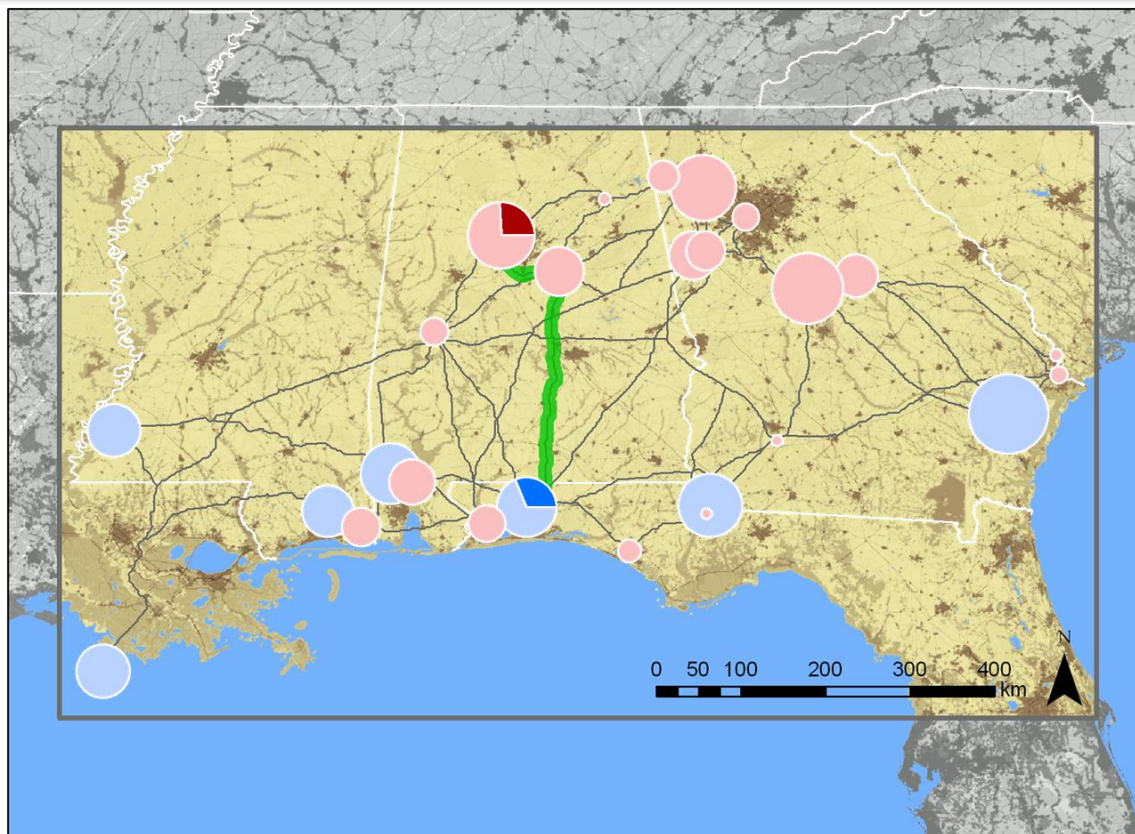
Dynamicism

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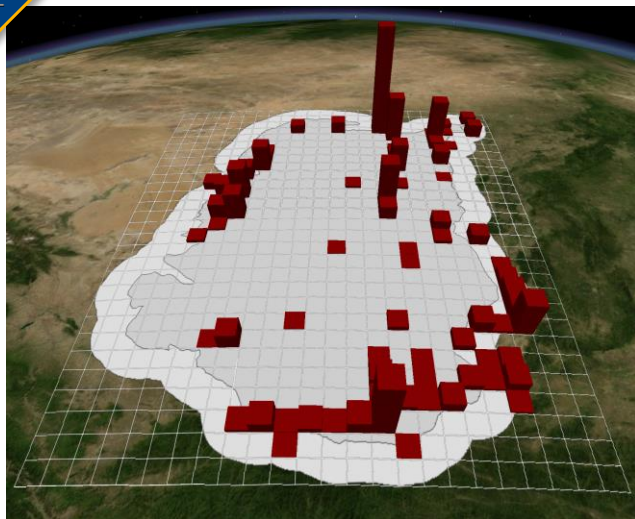
Dynamicism

Storage

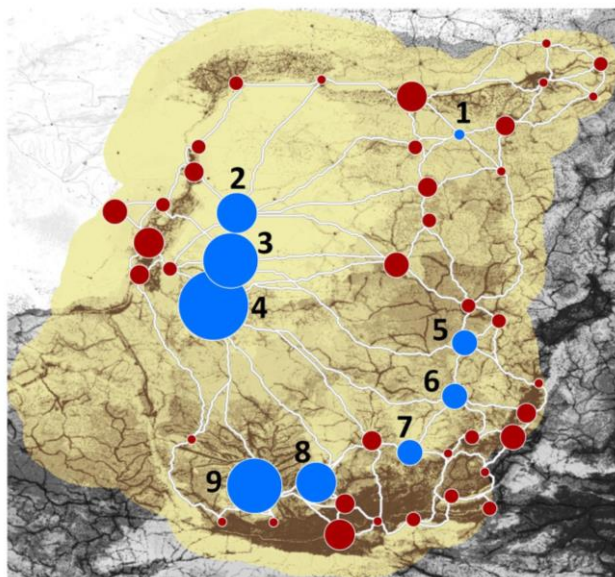
Transport

Capture

La Fin

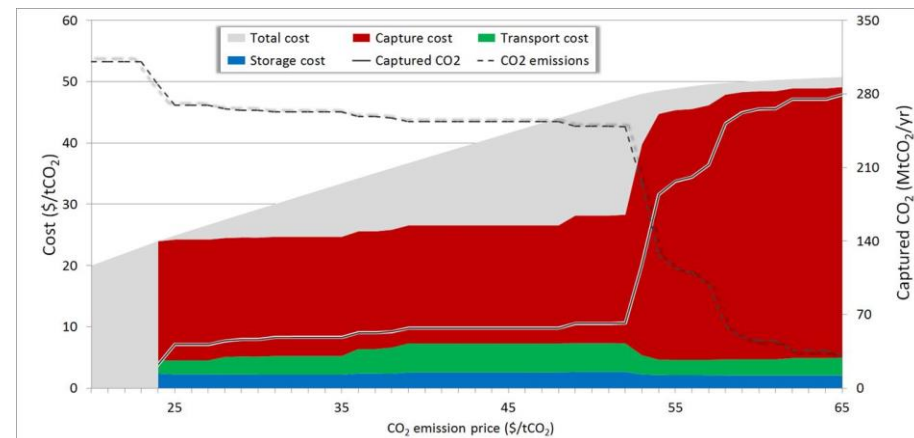


"Global" perspective of Ordos CO<sub>2</sub> emissions

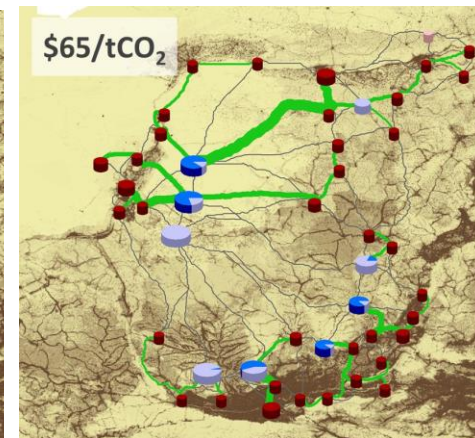
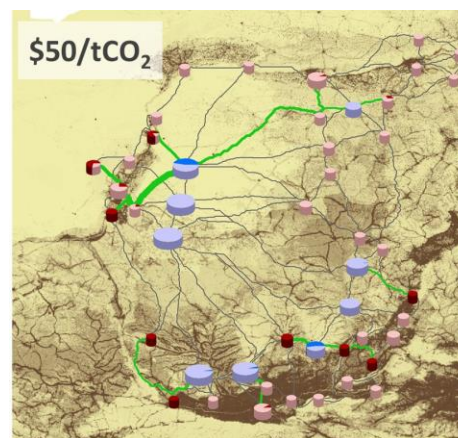


Candidate transport network, sources, & sinks

- multiple CCS scenarios driven by (a) CO<sub>2</sub> cap and (b) CO<sub>2</sub> emission prices
- understand how CO<sub>2</sub> capture, transport, and storage research interacts



Infrastructure response (cost & engineering) to a CO<sub>2</sub> tax



Geospatial infrastructure comparison for different CO<sub>2</sub> tax rates

# Oil sands: overview

## MENU

CCS

SimCCS

Case studies

SoCo

Ordos Basin

Oil sands

Dynamicism

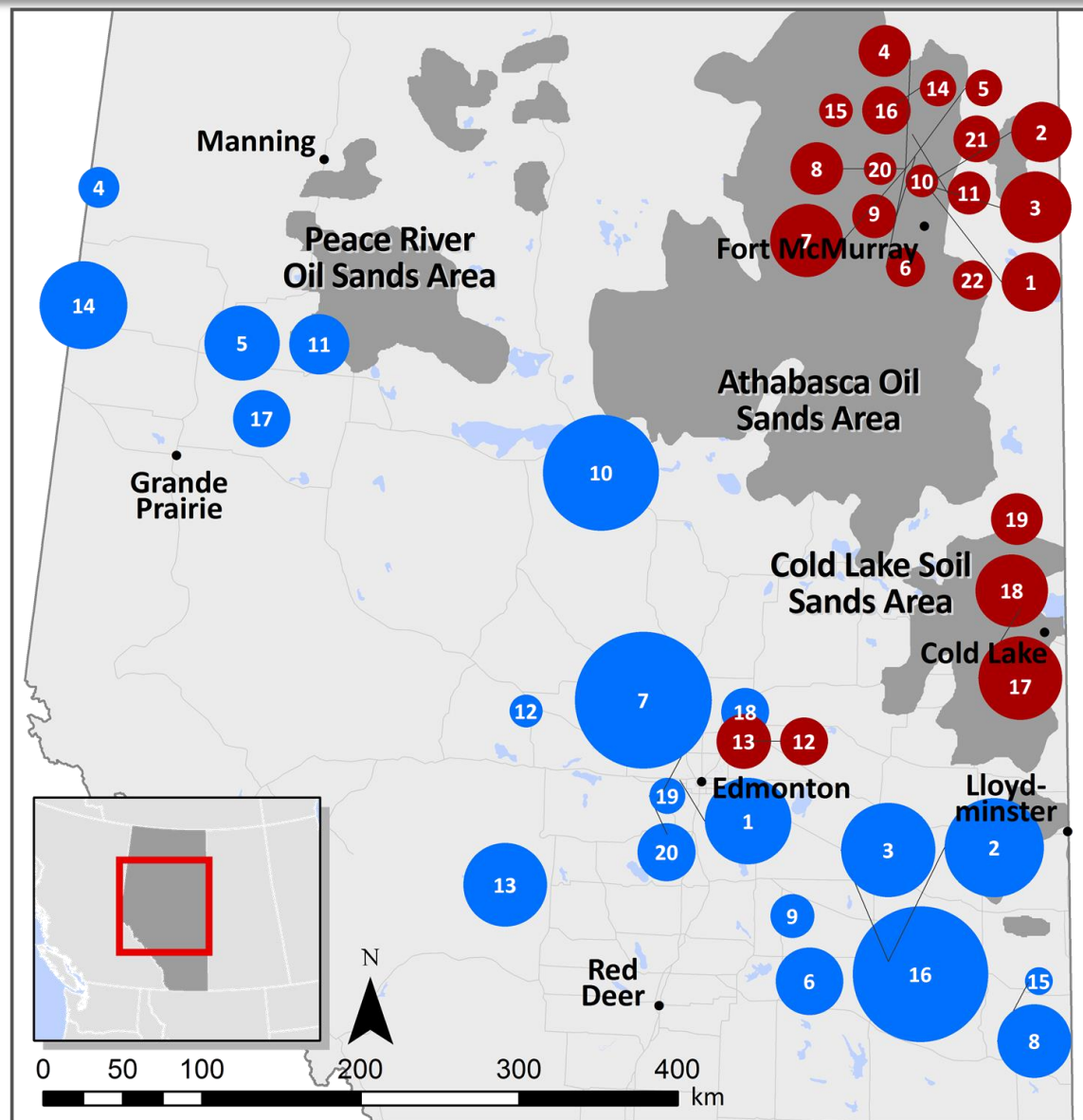
Storage

Transport

Capture

La Fin

- 22 sources; 39 MtCO<sub>2</sub>/yr
- Surface mining and *in situ* extraction
- CO<sub>2</sub> 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

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CCS

SimCCS

Case studies

SoCo

Ordos Basin

Oil sands

Dynamicism

Storage

Transport

Capture

La Fin

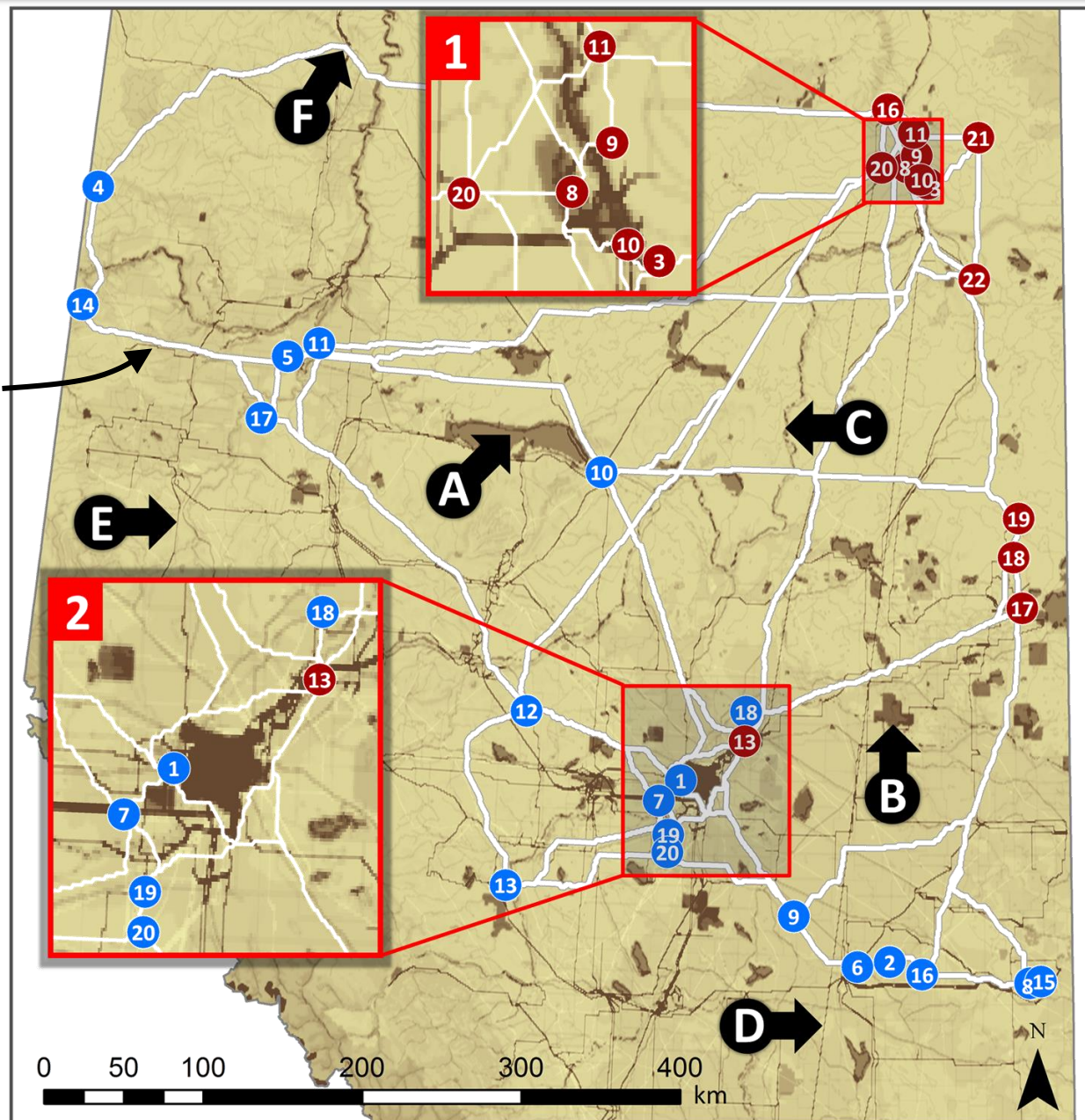
- generate candidate network linking sources and sinks

- A** Lake
- B** First Nation
- C** River
- D** Transmission line
- E** Road
- F** Pipeline ROW

### COST SURFACE



candidate network





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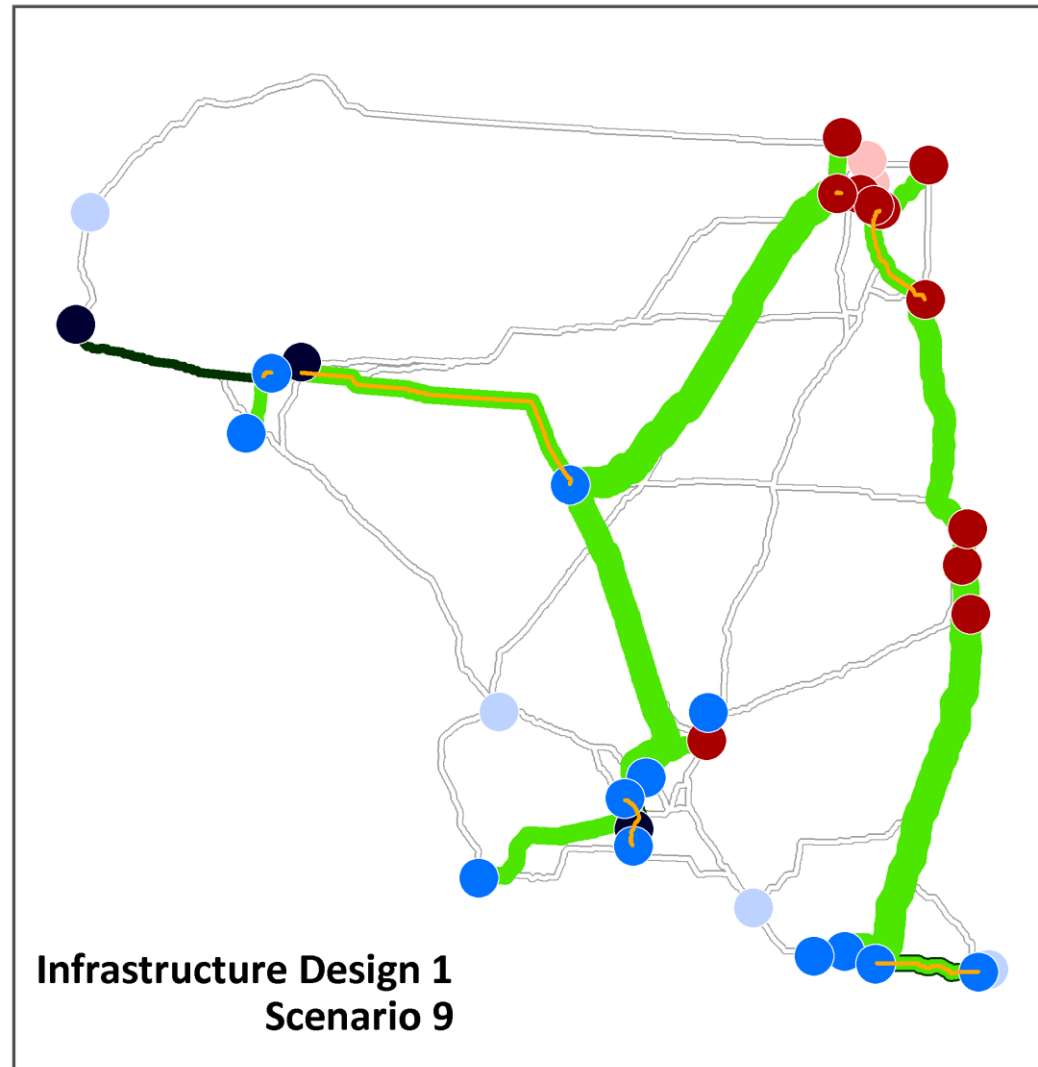
Transport

Capture

La Fin

## 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<sub>2</sub> transport and storage infrastructure, *International Journal of Greenhouse Gas Control* 8, 132-142.

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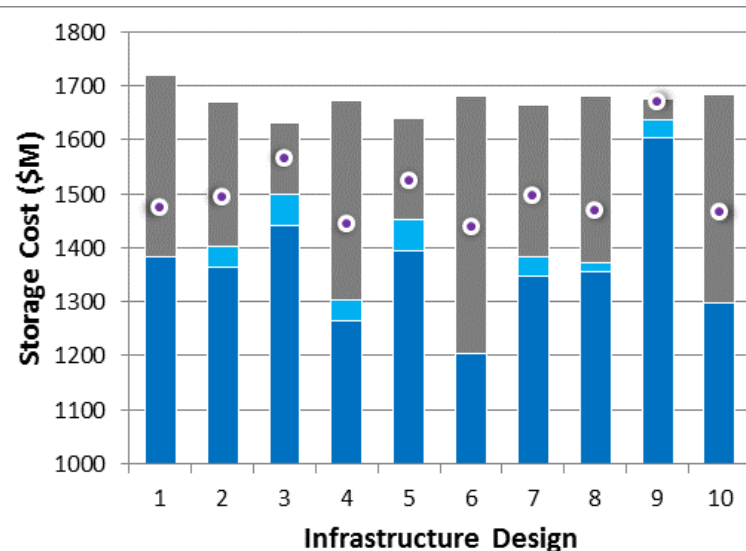
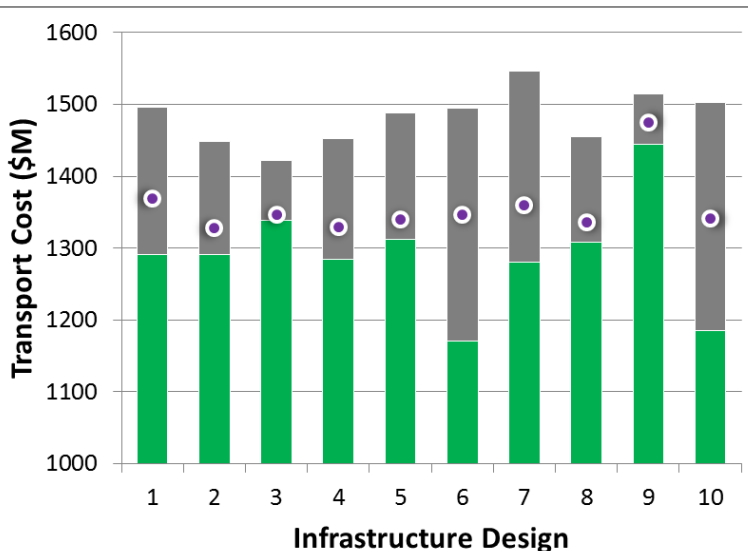
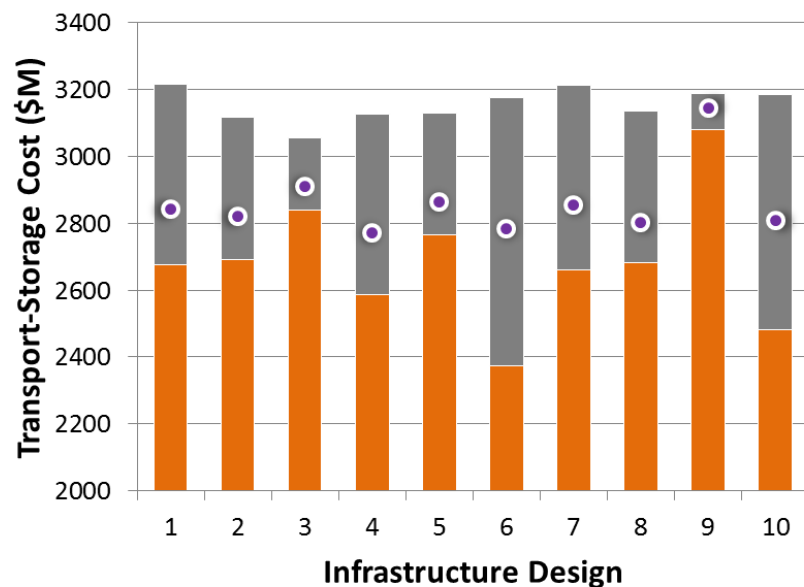
Transport

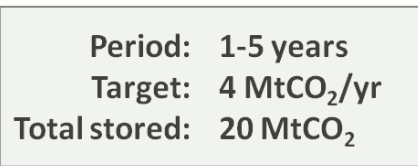
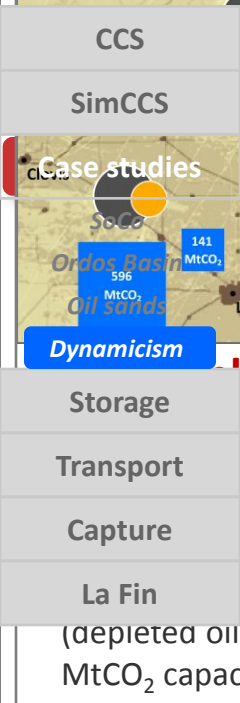
Capture

La Fin

## CO<sub>2</sub> Transport & storage

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





- *spatial optimization framework* for CO<sub>2</sub> capture and storage (CCS) infrastructure (capturing, transporting, injecting/storing CO<sub>2</sub>) through *multiple time periods*
- deploys CCS *networks* to meet a CO<sub>2</sub> *cap* (i.e., cap-and-trade) or in response to a *price/tax* to emit CO<sub>2</sub>
- *scientists, stakeholders, policy makers, general public*

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

- *overbuilds infrastructure* (e.g., pipelines, capture) in early periods to achieve *long-term economies of scale*
- *CCS costs rise through time* as more expensive CO<sub>2</sub> sources are brought online, *transport costs fall* through increased utilization (Chart A)
- *minimizes costs* across all time periods (Chart B)

## MENU

CCS

SimCCS

Case studies

Storage

Overview

Water

Uncertainty

Risk

CO<sub>2</sub>-EOR

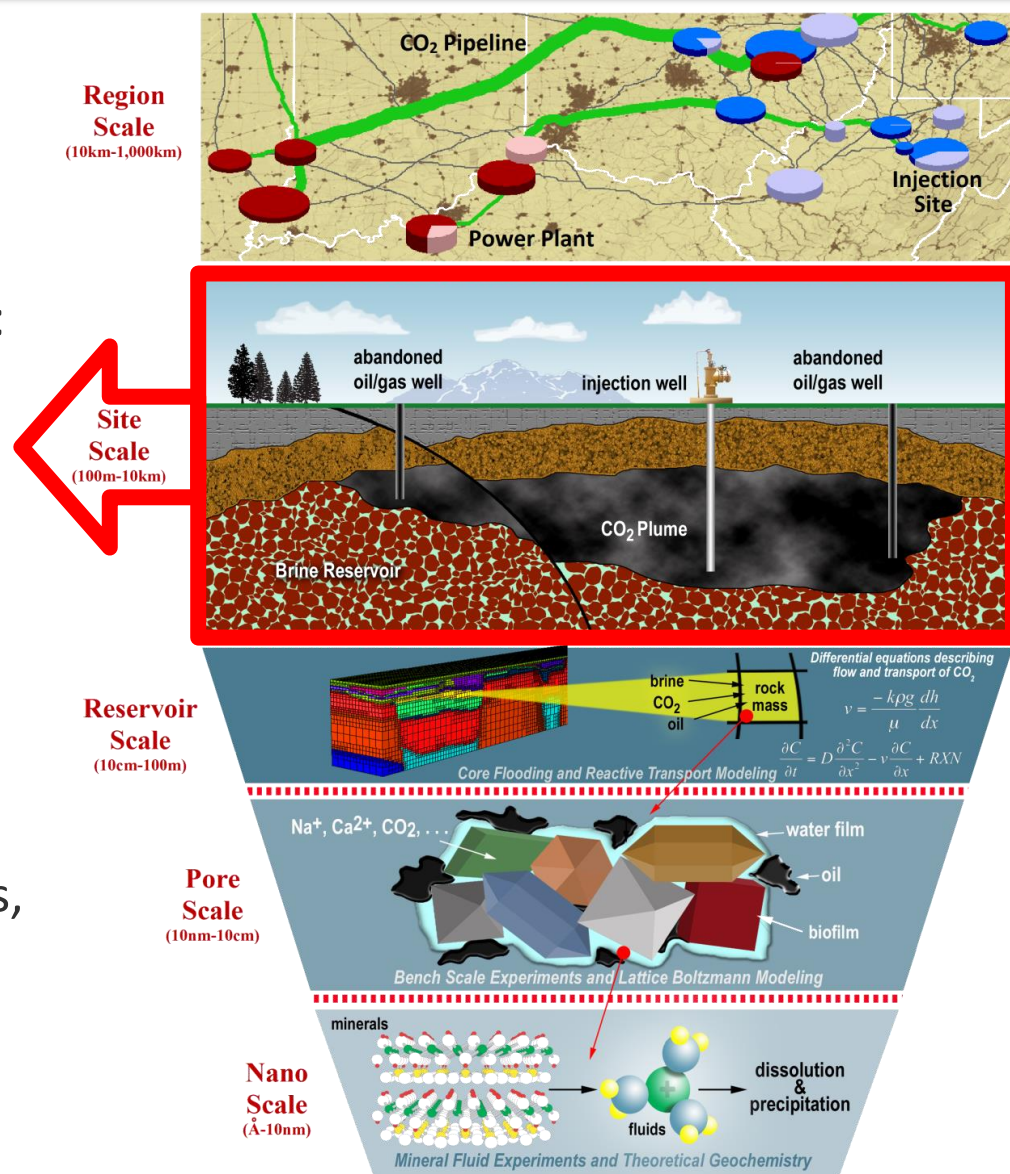
SCO<sub>2</sub>T

Transport

Capture

La Fin

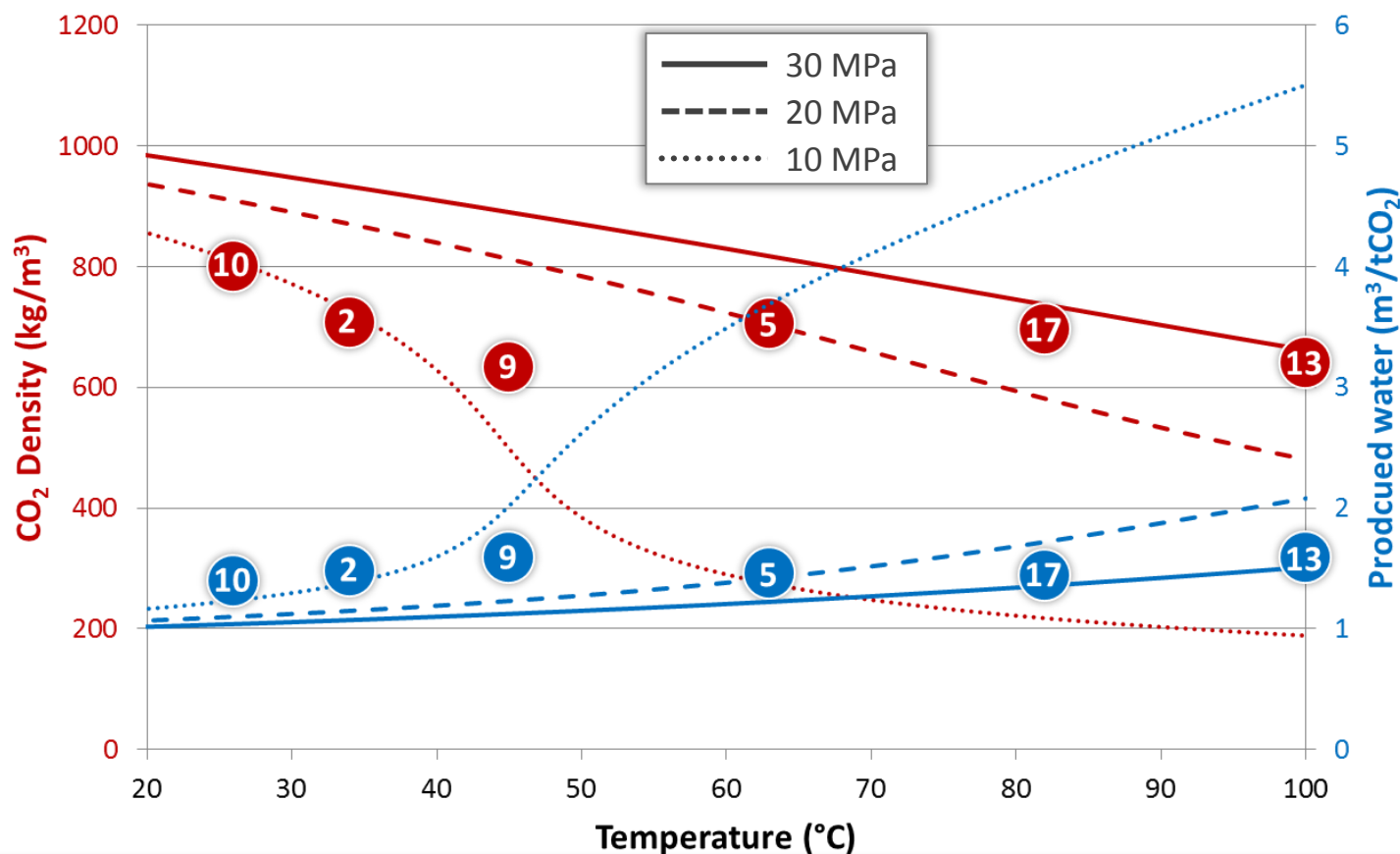
- **inputs:** formation depth, thickness, porosity, permeability, temperature, brine chemistry
- **computationally-efficient models:** based on fine-physics mechanistic (or process) models
- **outputs:** injectivity, well spacing storage capacity, and CO<sub>2</sub> plume characteristics
- **economics:** permitting, injection/production wells, pumping, distribution pipelines, pore space rights, monitoring, water treatment...



\* Middleton et al. (2012) The cross-scale science of CO<sub>2</sub> capture and storage: from pore scale to regional scale, *Energy & Environmental Science* 5, 7328-7345.

## Extracted water

- enhance storage, CO<sub>2</sub> plume management, reduce seismicity risks
- function of depth/pressure and temperature
- significant impact on engineering and costs





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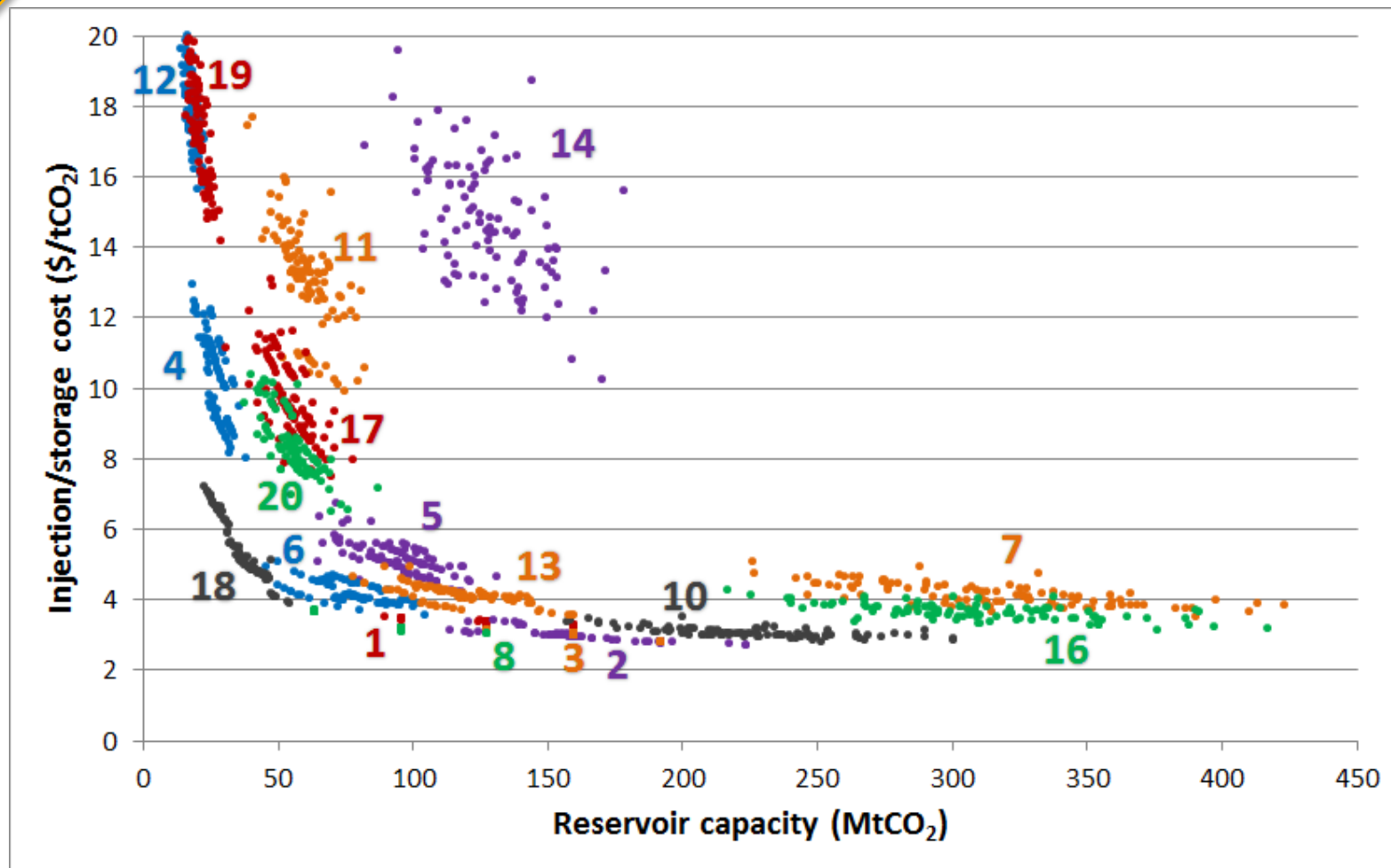
CO<sub>2</sub>-EOR

SCO<sub>2</sub>T

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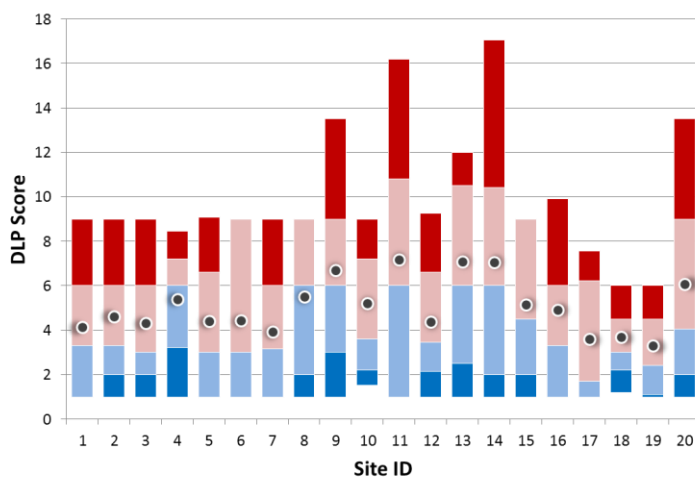
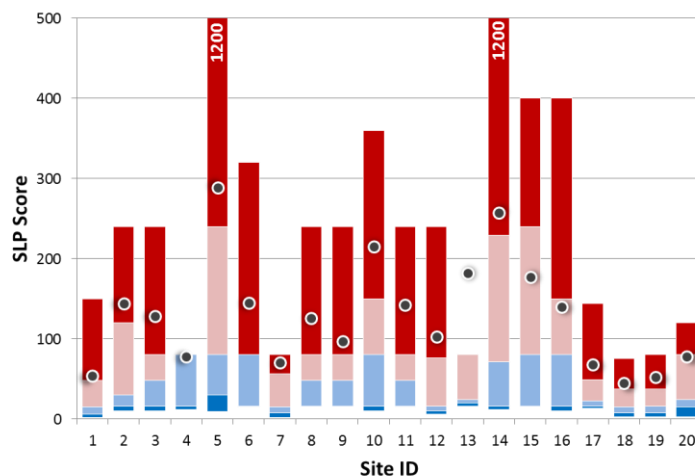
**UNCERTAINTY:** formation thickness, permeability, and porosity

**EFFECT:** available volume, injectivity, well spacing

**IMPACT:** storage capacity, injection-storage cost

## Leakage potential: shallow (SLP) and deep (DLP)<sup>1,2</sup>

- 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

<sup>1</sup> Watson and Bachu (2007) Evaluation of the Potential for Gas and CO<sub>2</sub> Leakage along Wellbores, SPE Paper #: 106817

<sup>2</sup> Watson and Bachu (2008) Identification of Wells with High CO<sub>2</sub>-Leakage Potential in Mature Oil Fields Developed for CO<sub>2</sub>-Enhanced Oil Recovery, SPE Paper #: 112924

# Coupled CO<sub>2</sub> sequestration/EOR systems

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CO<sub>2</sub>-EOR

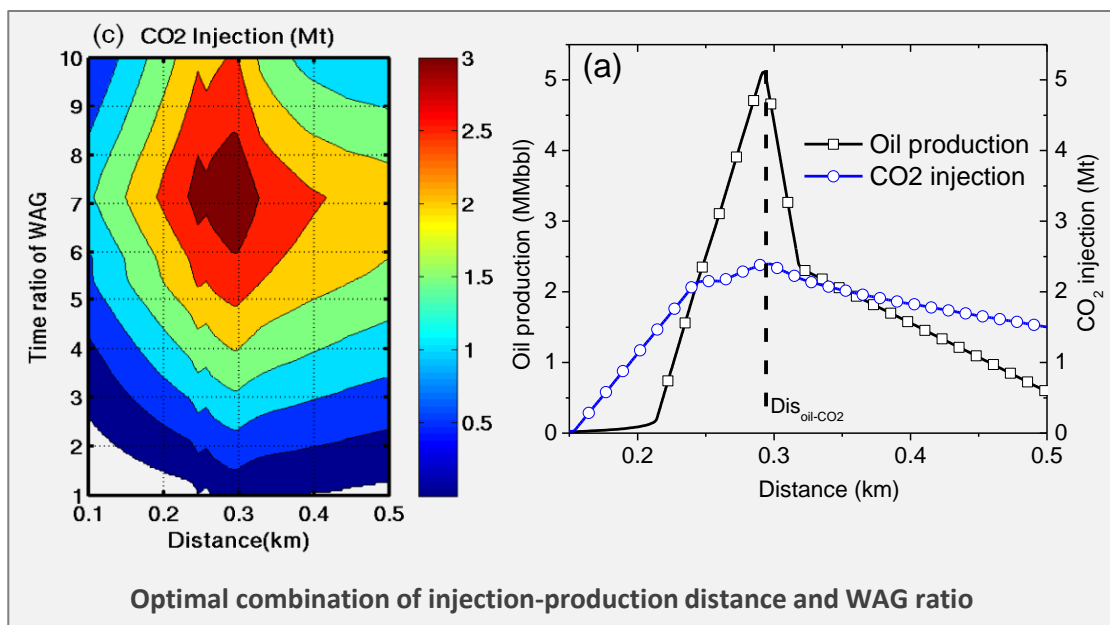
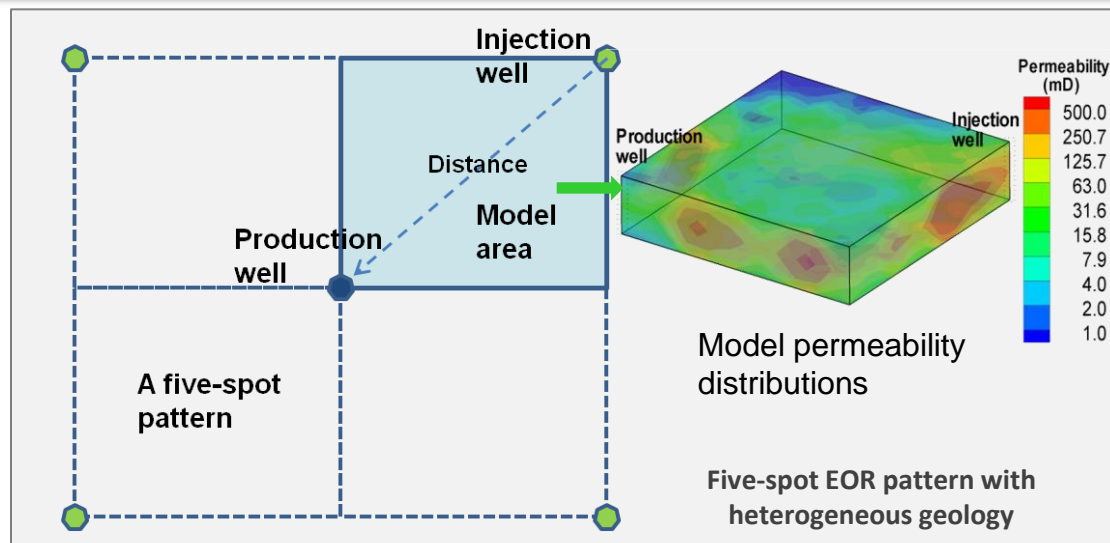
SCO<sub>2</sub>T

Transport

Capture

La Fin

- framework to co-estimate CO<sub>2</sub> storage and oil production
- optimize site engineering including WAG ratio and well spacing
- formally track uncertainty and parameter importance
- economics



Dai, Middleton, *et al.* (2014) An integrated framework for optimizing CO<sub>2</sub> sequestration and enhanced oil recovery, *Environmental Science & Technology Letters* 1, 49-54.

# Coupled CO<sub>2</sub> sequestration/EOR systems

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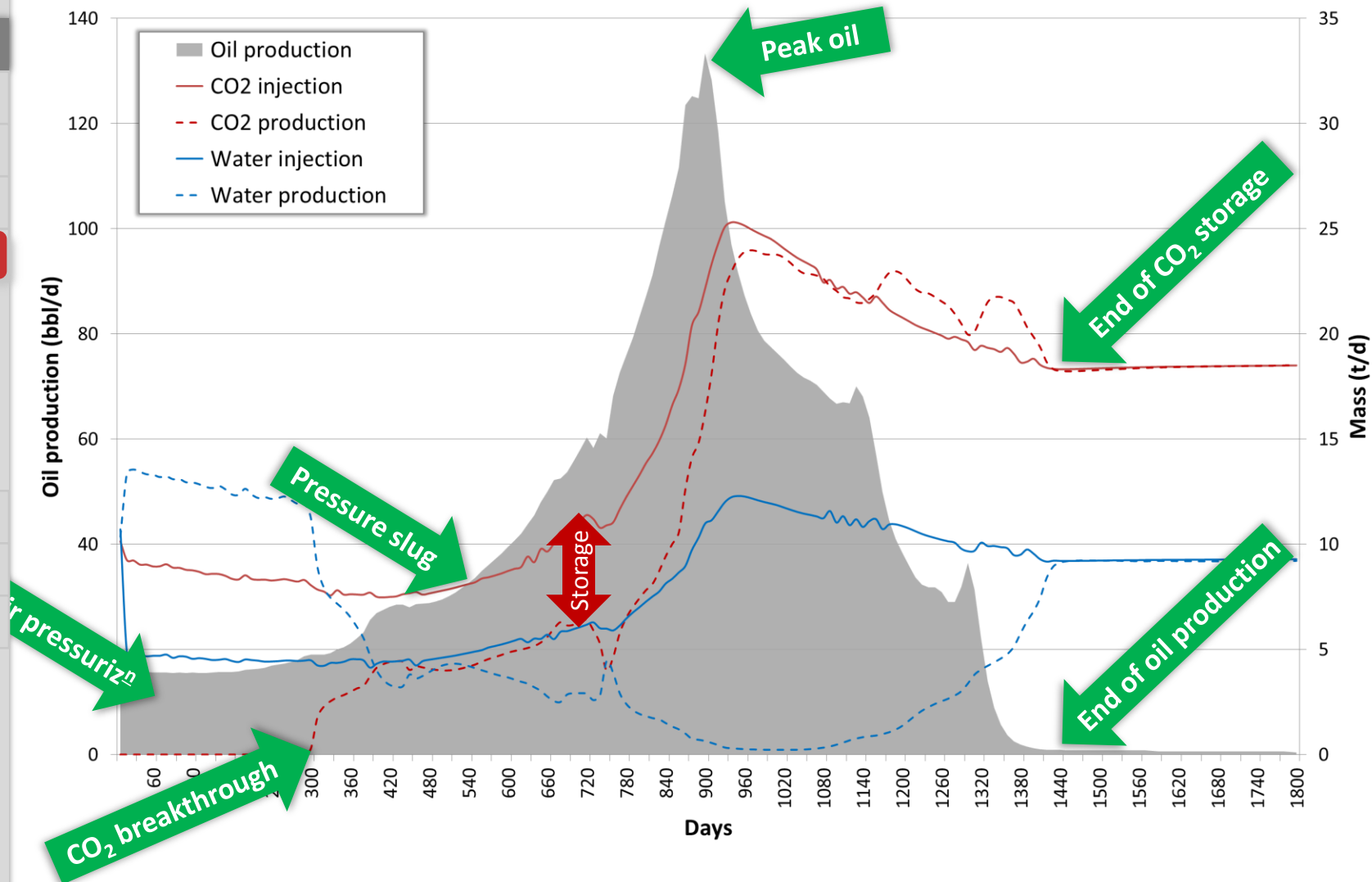
CO<sub>2</sub>-EOR

SCO<sub>2</sub>T

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Dai, Middleton, *et al.* (2013) An integrated framework for optimizing CO<sub>2</sub> sequestration and enhanced oil recovery, *Environmental Science & Technology Letters* 1, 49-54.

## SCO<sub>2</sub>T (Sequestration of CO<sub>2</sub> Tool)

- distributable CO<sub>2</sub> sequestration/EOR framework; VBA+Excel
- present/future: CO<sub>2</sub> fracturing for shale gas

**MENU**

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CO<sub>2</sub>-EOR

**SCO<sub>2</sub>T**

Transport

Capture

La Fin

SCO<sub>2</sub>T v3.3.xlsx - Microsoft Excel

File

Home

Insert

Layout

Formulas

Data

Review

View

Developer

Add-ins

Account

Cut

Copy

Format Painter

Clipboard

Calibri

11

A

A'

B

B'

C

C'

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M

M'

N

N'

O

O'

P

P'

Q

Q'

R

R'

S

S'

T

T'

U

U'

V

V'

W

W'

X

X'

Y

Y'

Z

Z'

AA

AA'

AB

AB'

Font

Alignment

Number

Conditional Formatting

Format

Normal

Red

Good

Neutral

Calculation

Check Cell

Exploratory...

Input

Linked Cell

Note

Insert

Delete

Format

Autosum

Fill

Clear

Sort & Filter

Find & Select

Cells

Editing

O2O

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42

43

44

45

46

47

48

49

50

Parameter

Min

Max

Step

Mean

Std Dev

Normal distribution

Normal distribution

Maximum number of points in chart

Interest rate (%)

Capital charge factor

Water treatment & disposal cost (\$/m<sup>3</sup>)

Number of water wells per injection well

Include pump costs per well

Depth (m)

100.00

3000.00

10.00

2362.00

0.10

0.00

0.00

1000

0.104

0.111

0.00

0.00

Defined hydrostatic pressure (MPa)

-1.00

-1.00

1.00

-1.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Thickness (m)

20.00

20.00

20.00

7.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Permeability (mD)

1.00E-13

1.00E-13

1.00E-13

1.00E-14

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Porosity (fraction)

0.12

0.12

0.12

0.10

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Temperature (°C)

-1.0

-1.0

1.0

-1.0

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Area (km<sup>2</sup>)

10000.00

10000.00

1000.00

256.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Residual water saturation (fraction)

0.50

0.50

0.50

0.50

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Defined lithostatic pressure (MPa)

-1.00

-1.00

1.00

-1.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Average rock density (kg/m<sup>3</sup>)

2650.00

2650.00

2650.00

2650.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Average rock porosity (fraction)

0.20

0.20

0.20

0.20

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Defined maximum injection pressure (MPa)

-1.00

-1.00

1.00

-1.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Maximum injection pressure (as fraction)

0.75

0.75

0.75

0.75

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Maximum well injection rate (MCO<sub>2</sub>/yr)

1.00

1.00

1.00

1.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Maximum site injection rate (MCO<sub>2</sub>/yr)

-1.00E+00

-1.00

1.00

-1.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Maximum number of wells

-1.00E+00

-1.00

1.00

-1.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Injection period (years)

3.00E+01

30.00

30.00

30.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

0.00

Realizations

Combinations

Normal

Run data

25.00

35.20

Model inputs parameters

Model outputs

ID

Depth (m)

Hydrostatic pressure (MPa)

Thickness (m)

Permeability (mD)

Porosity (fraction)

Temperature (°C)

Area (km<sup>2</sup>)

Residual water saturation (fraction)

Lithostatic pressure (MPa)

Maximum injection pressure (MPa)

Injection period (years)

CO<sub>2</sub> density (kg/m<sup>3</sup>)

CO<sub>2</sub> viscosity (Pa-s)

CO<sub>2</sub> compressibility (Pa<sup>-1</sup>)

Water density (kg/m<sup>3</sup>)

Water viscosity (Pa-s)

Water production rate (m<sup>3</sup>/CO<sub>2</sub>)

CO<sub>2</sub> phase (text)

Water phase (text)

No bounds

Bound: well capacity

Bounded by well and site restrictions

Well injection rate (MCO<sub>2</sub>/yr)

Plume radius (m)

Well injection rate (MCO<sub>2</sub>/yr)

Plume radius (m)

Well injection rate (MCO<sub>2</sub>/yr)

Plume radius (m)

Number of wells

Reservoir storage capacity (MCO<sub>2</sub>)

1-1

1086.08

10.67

189.25

9.87E-15

0.10

45.75

45.75

0.50

23.61

17.77

50.0

604.12

4.54E-05

2.25E-07

995.29

6.10E-04

1.65

1

1

0.61

4.856

0.61

4.856

0.61

4.856

0.61

1.790

15.51

2-1

3964.57

38.88

430.73

9.87E-15

0.10

125.44

1658.70

0.50

86.31

64.73

50.0

666.63

5.56E-05

1.37E-08

957.27

2.31E-04

1.44

1

1

18.82

9.114

1.00

2.147

0.99

2.139

103

5312.62

5312.62

3-1

3987.45

39.10

527.15

9.87E-15

0.10

126.09

1730.00

0.50

86.81

65.11

50.0

666.32

5.56E-05

1.36E-08

956.82

2.30E-04

1.44

1

1

22.27

9.136

1.00

1.936

0.99

1.930

132

6558.30

6558.30

4-1

4365.28

42.81

525.47

9.87E-15

0.10

126.62

1784.90

0.50

95.04

71.28

50.0

667.31

5.63E-05

1.23E-08

950.11

2.12E-04

1.43

1

1

26.03

9.447

1.00

1.852

1.00

1.850

144

7339.21

7339.21

5-1

3872.34

38.41

572.10

9.87E-15

0.10

66.17

1207.60

0.50

40.87

30.85

50.0

650.61

5.13E-05

3.58E-08

987.77

4.30E-04

1.52

1

1

5.91

6.511

1.00

2.678

1.00

2.674

46

2392.22

2392.22

6-1

1895.94

18.59

444.43

9.87E-15

0.10

66.70

1009.30

0.50

41.28

30.96

50.0

651.80

5.15E-05

3.51E-08

987.58

4.27E-04

1.52

1

1

4.68

6.540

1.00

3.022

0.98

2.994

32

1570.27

1570.27

7-1

1853.64

18.18

316.31

9.87E-15

0.10

65.49

1028.30

0.50

40.36

30.27

50.0

651.08

5.13E-05

3.62E-08

988.06

4.35E-04

1.52

1

1

3.20

6.466

1.00

3.617

0.97

3.564

23

1116.71

1116.71

8-1

3181.15

31.22

469.55

9.87E-15

0.10

393.25

3862.90

0.50

69.30

51.97

50.0

663.18

5.43E-05

1.77E-08

970.06

2.81E-04

1.47

1

1

13.21

6.352

1.00

2.295

0.99

2.289

101

5003.85

5003.85

9-1

4175.59

40.99

444.42

9.87E-15

0.10

131.55

1858.70

0.50

90.99

68.24

50.0

666.83

5.59E-05

1.29E-08

953.41

2.20E-04

1.43

1

1

20.41

9.299

1.00

2.058

1.00

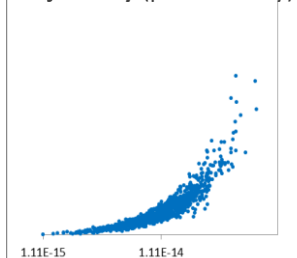
2.056

125

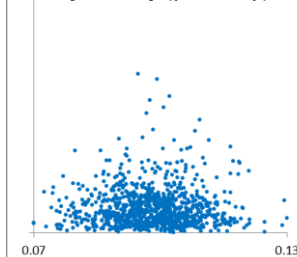
6234.86

6234.86

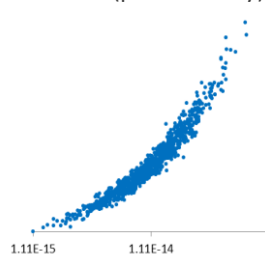
Injctivity (permeability)



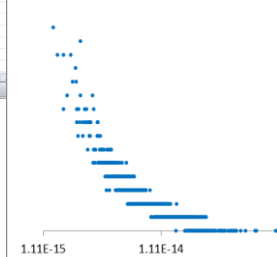
Injctivity (porosity)



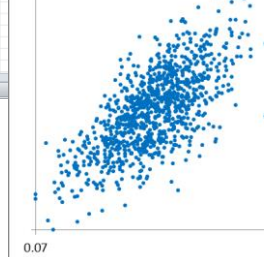
Plume (permeability)



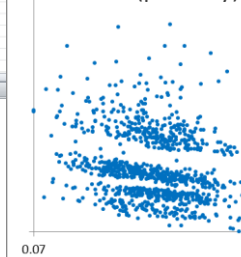
# wells (permeability)



Capacity (porosity)



Cost (porosity)

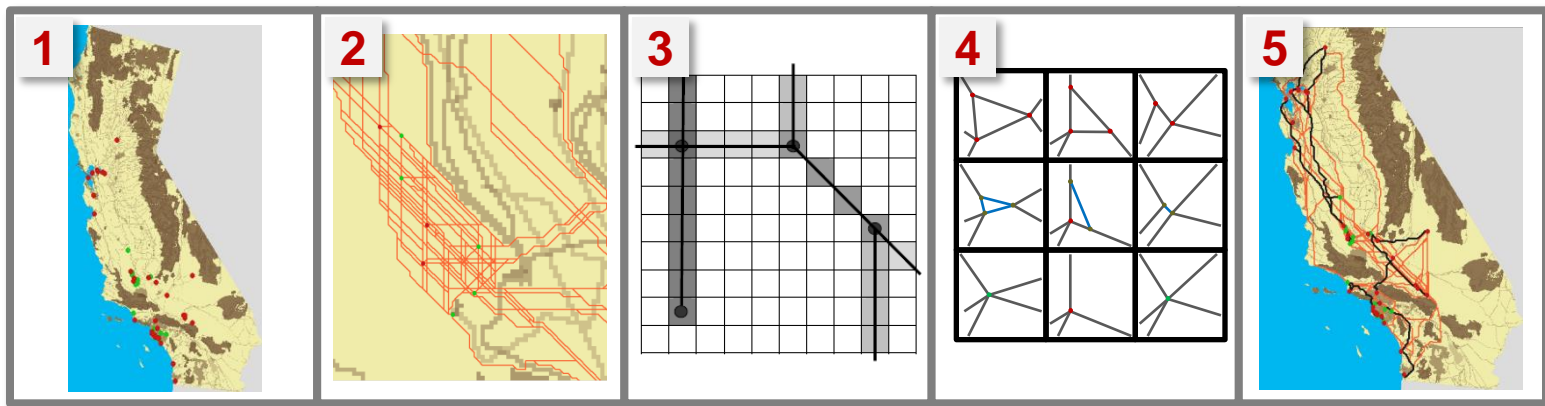


# SCO<sub>2</sub>T



## 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<sub>2</sub> capture and storage optimization problem, *Computers, Environment and Urban Systems* 36, 18-29.

## MENU

CCS

SimCCS

Case studies

Storage

Transport

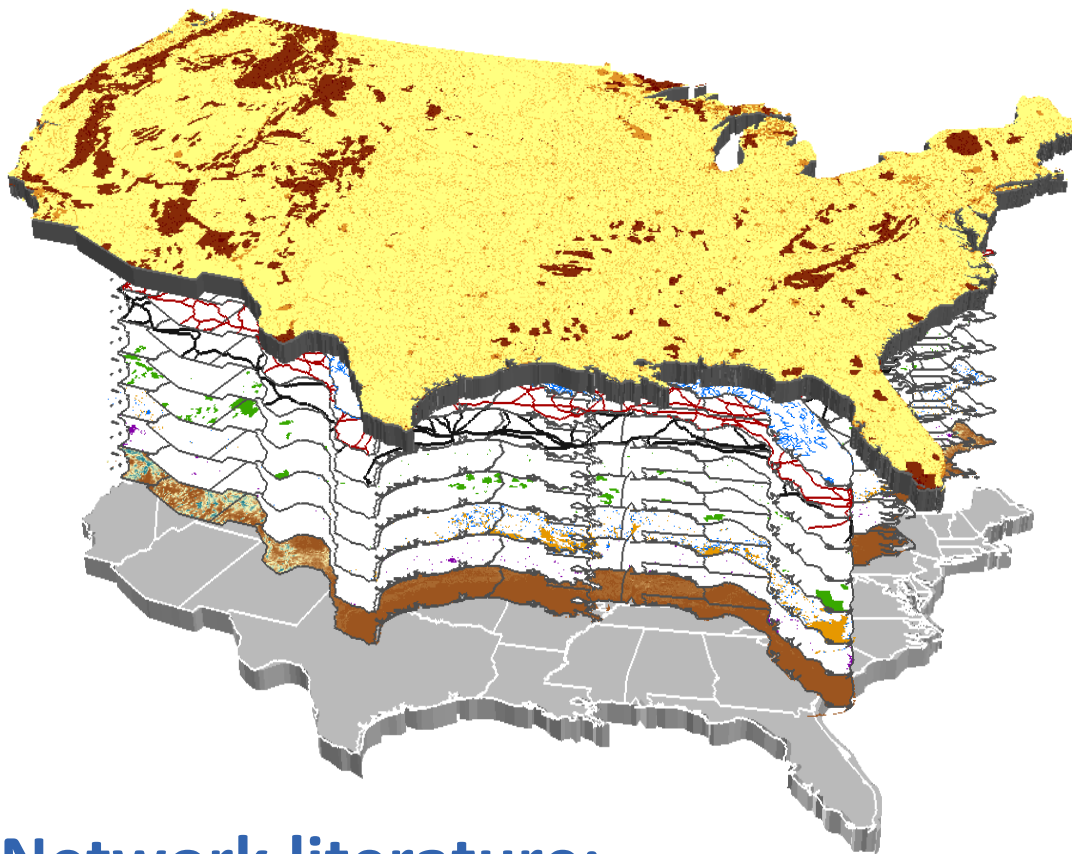
Overview

Network

Pipelines

Capture

La Fin



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

### MENU

CCS

SimCCS

Case studies

Storage

Transport

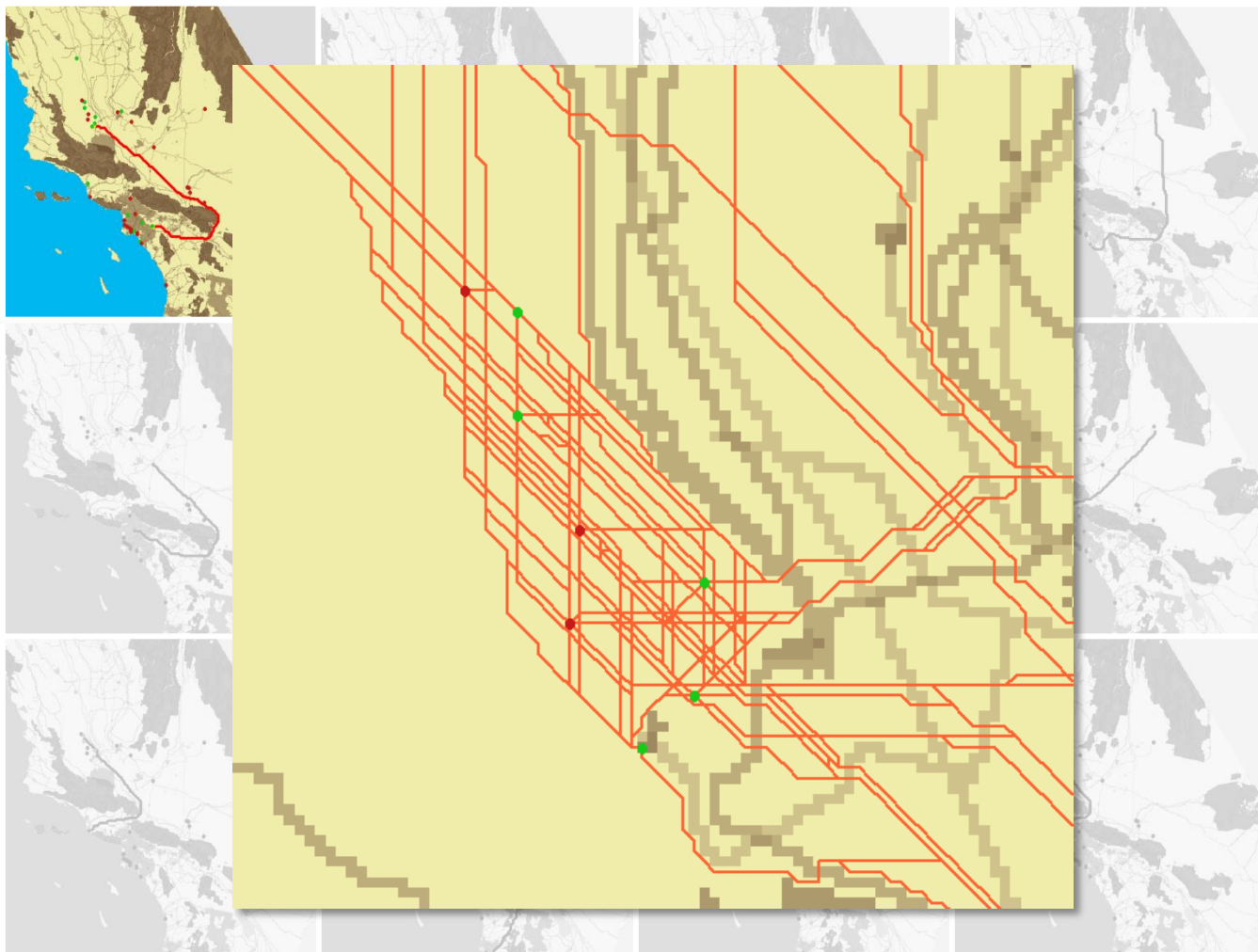
Overview

Network

Pipelines

Capture

La Fin



# STEP 3: Vector Network Extraction

## MENU

CCS

SimCCS

Case studies

Storage

Transport

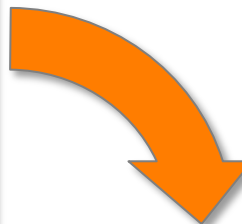
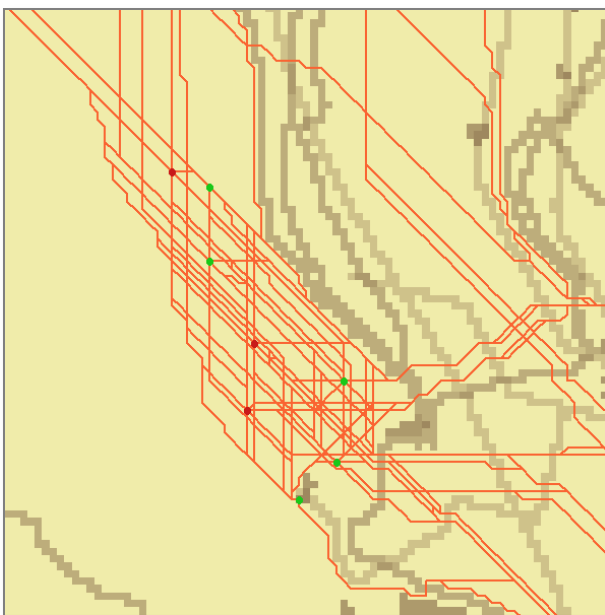
Overview

Network

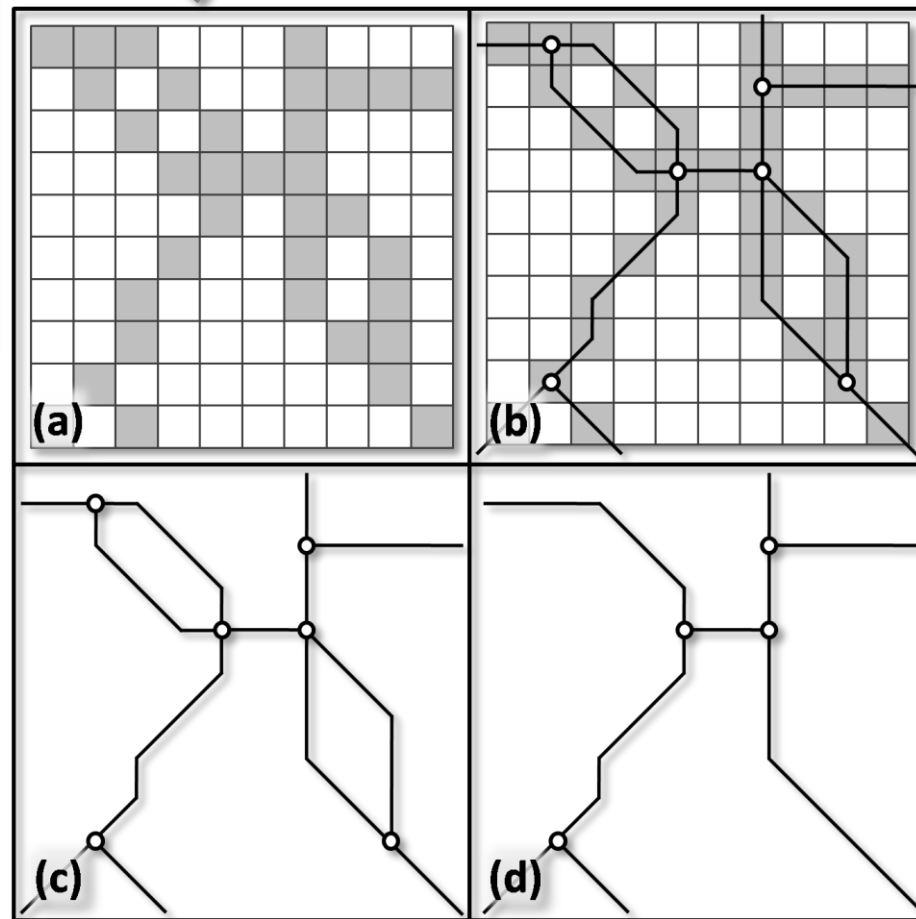
Pipelines

Capture

La Fin



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



# STEP 4: Raw Network Refinement

## MENU

CCS

SimCCS

Case studies

Storage

Transport

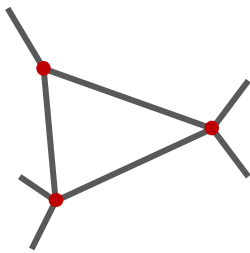
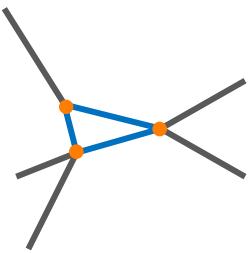
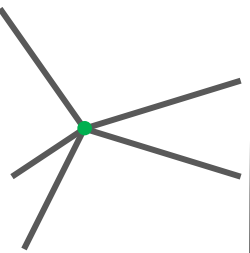
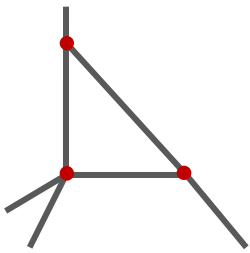
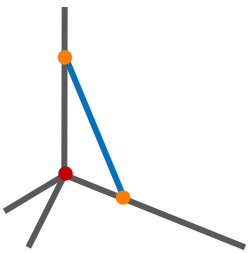
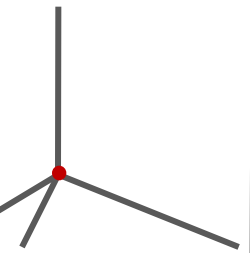
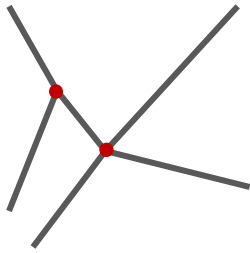
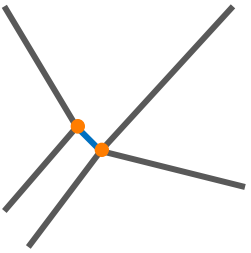
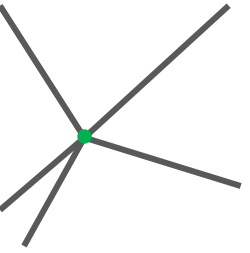
Overview

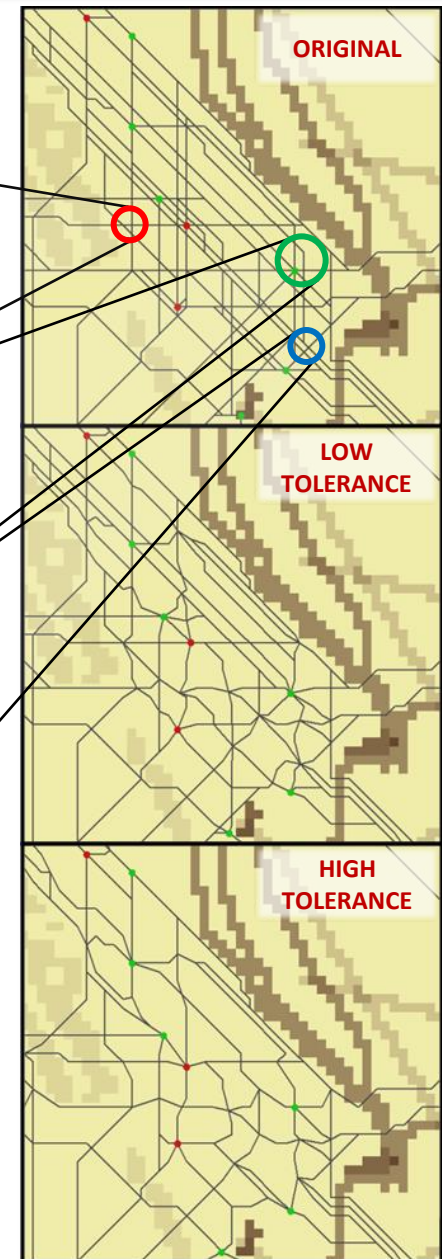
Network

Pipelines

Capture

La Fin

	EXCEEDS TOLERANCE (NO CHANGE)	WITHIN TOLERANCE (BEFORE CHANGE)	WITHIN TOLERANCE (AFTER CHANGE)
COLLAPSE TRIANGLES			
CUT TRIANGLE SIDES			
MERGE NODES			



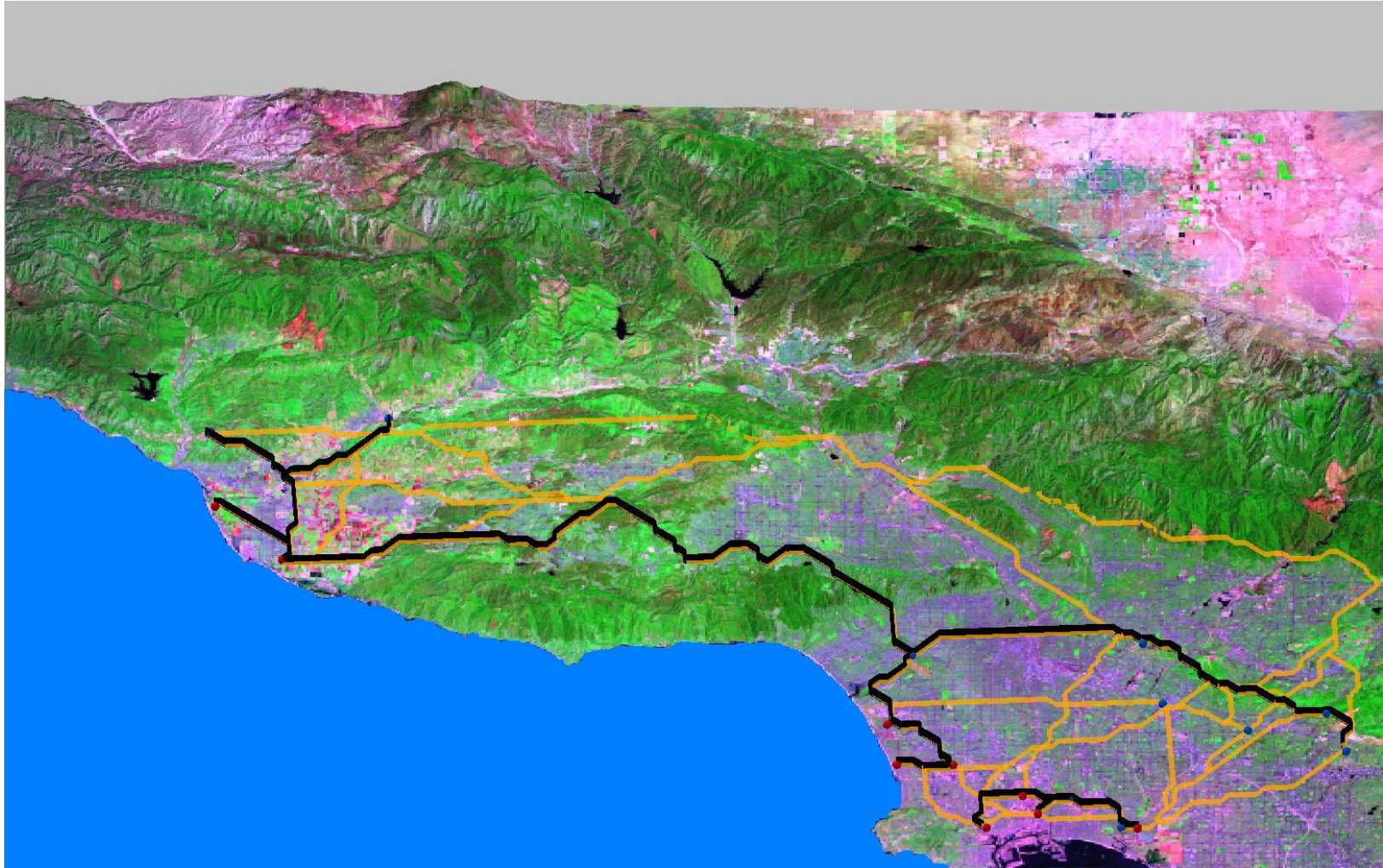
## Refinement:

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



## *SimCCS:*

- Los Angeles basin example



### MENU

CCS

SimCCS

Case studies

Storage

Transport

Overview

Network

Pipelines

Capture

La Fin

## MENU

CCS

SimCCS

Case studies

Storage

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Overview

Network

Pipelines

Capture

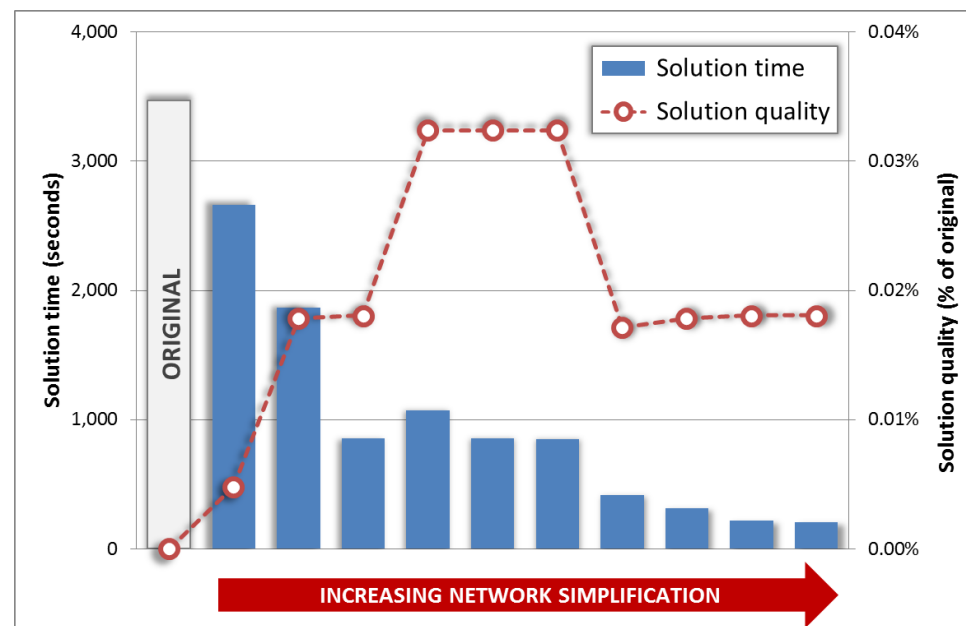
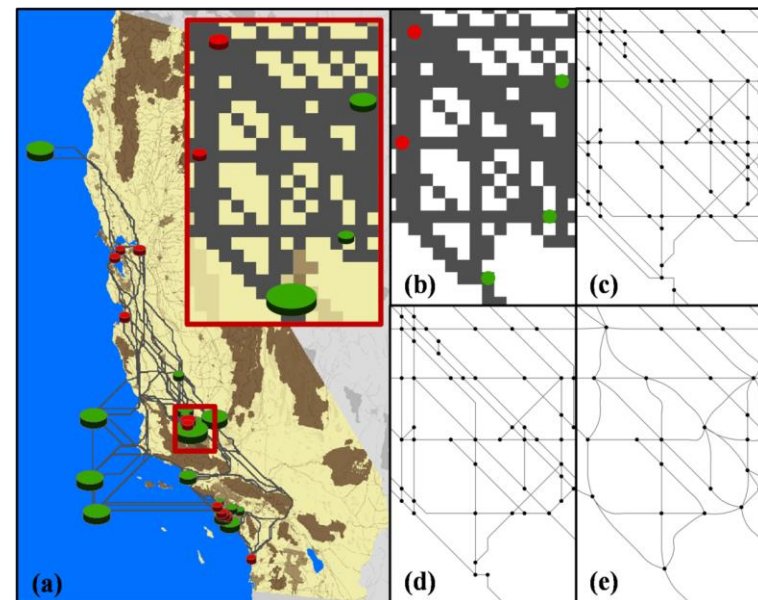
La Fin

	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<sub>2</sub> capture & storage optimization problem, *Computers, Environment and Urban Systems* 36, 18-29.



# Pipelines: precisely wrong vs. approximately right?

## MENU

CCS

SimCCS

Case studies

Storage

Transport

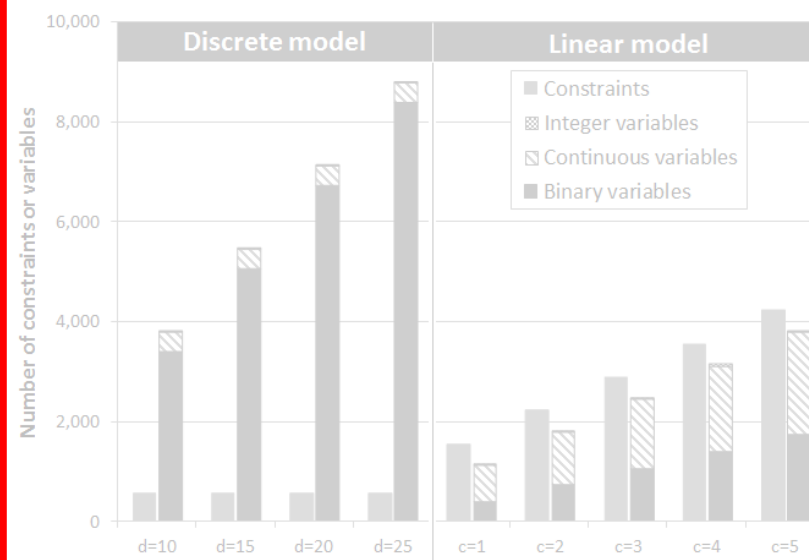
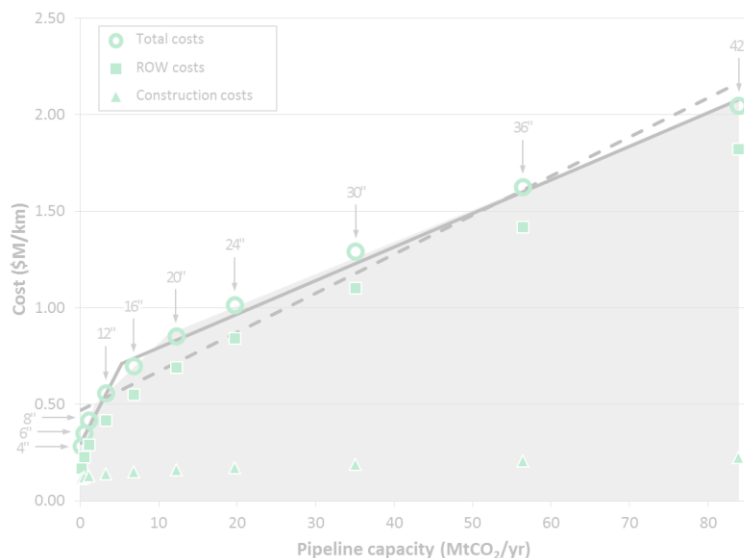
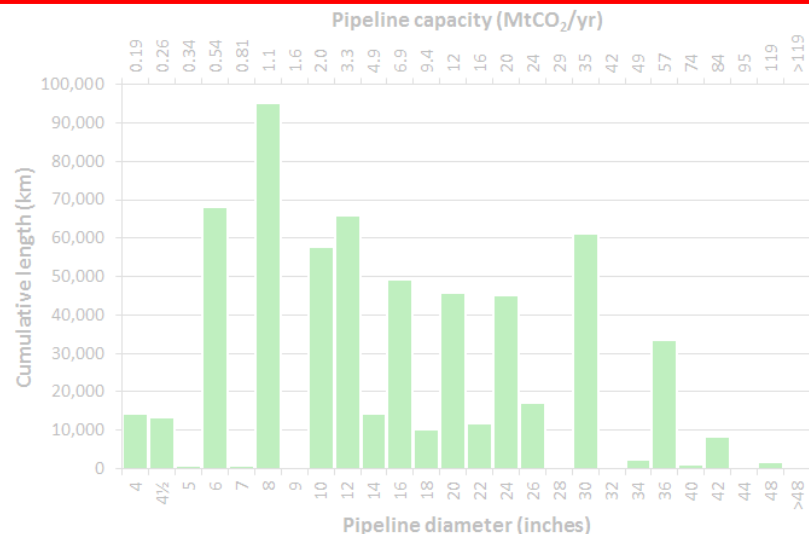
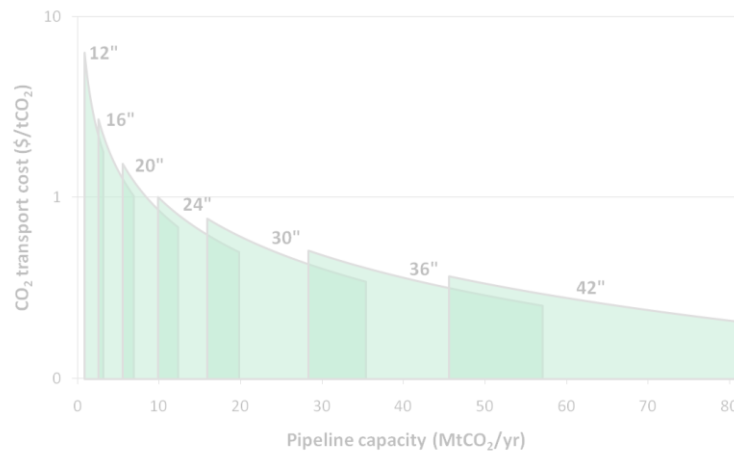
Overview

Network

Pipelines

Capture

La Fin



\* **Middleton (2013)** A new optimization approach to energy network modeling: anthropogenic CO<sub>2</sub> capture coupled with enhanced oil recovery, *International Journal of Energy Research* 37, 1794-1810.

# Pipelines: precisely wrong vs. approximately right?

## MENU

CCS

SimCCS

Case studies

Storage

Transport

Overview

Network

Pipelines

Capture

La Fin

## LINEAR

## DISCRETE

Pipeline diameter (inches)	Pipeline capacity (MtCO <sub>2</sub> /yr)	Actual cost (\$M/km)	One piece		Two pieces		Three pieces	
			Estimate (\$M/km)	Error (%)	Estimate (\$M/km)	Error (%)	Estimate (\$M/km)	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<sub>2</sub> capture coupled with enhanced oil recovery, *International Journal of Energy Research* 37, 1794-1810.



## MENU

CCS

SimCCS

Case studies

Storage

Transport

**Capture**

**Variability**

Boilers

Cost

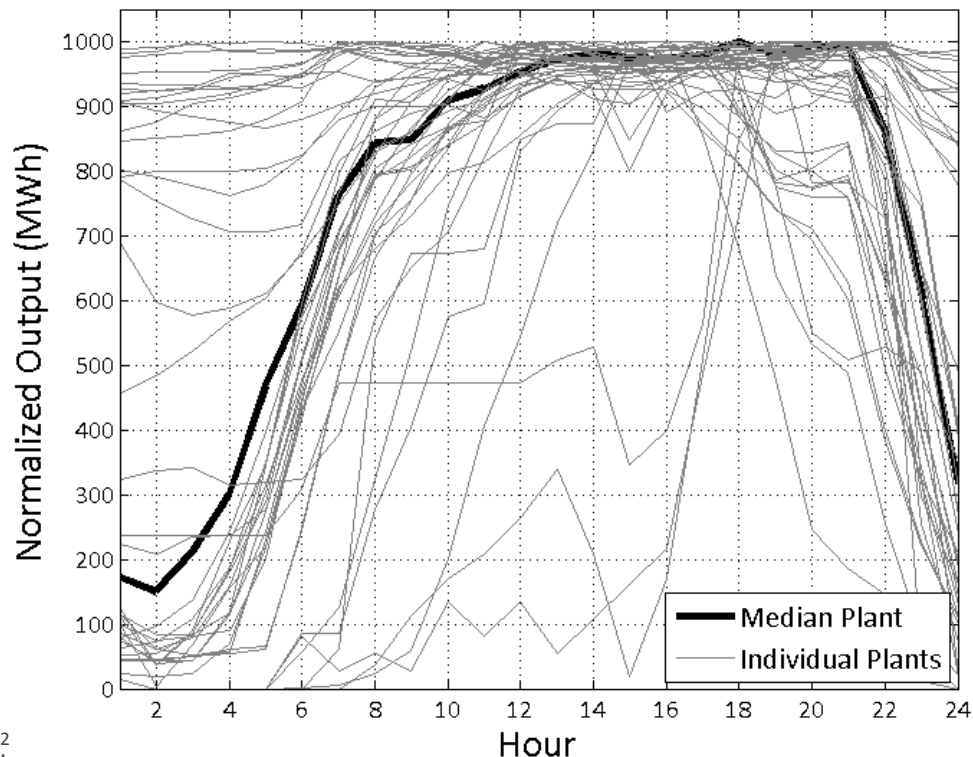
La Fin

## 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<sub>2</sub> capture and storage: Variable electricity generation and fossil fuel power. *Applied Energy* 108, 66-73.



# Variable generation and CO<sub>2</sub> capture

- CO<sub>2</sub> capture profile for the median 1000 MWyr gas plant
- emits 3.8 MtCO<sub>2</sub>/yr at maximum rate, 90% capture rate
- efficiency of capture equipment changes with capacity
- economic model: includes CO<sub>2</sub> tax and “make-up” electricity

## MENU

CCS

SimCCS

Case studies

Storage

Transport

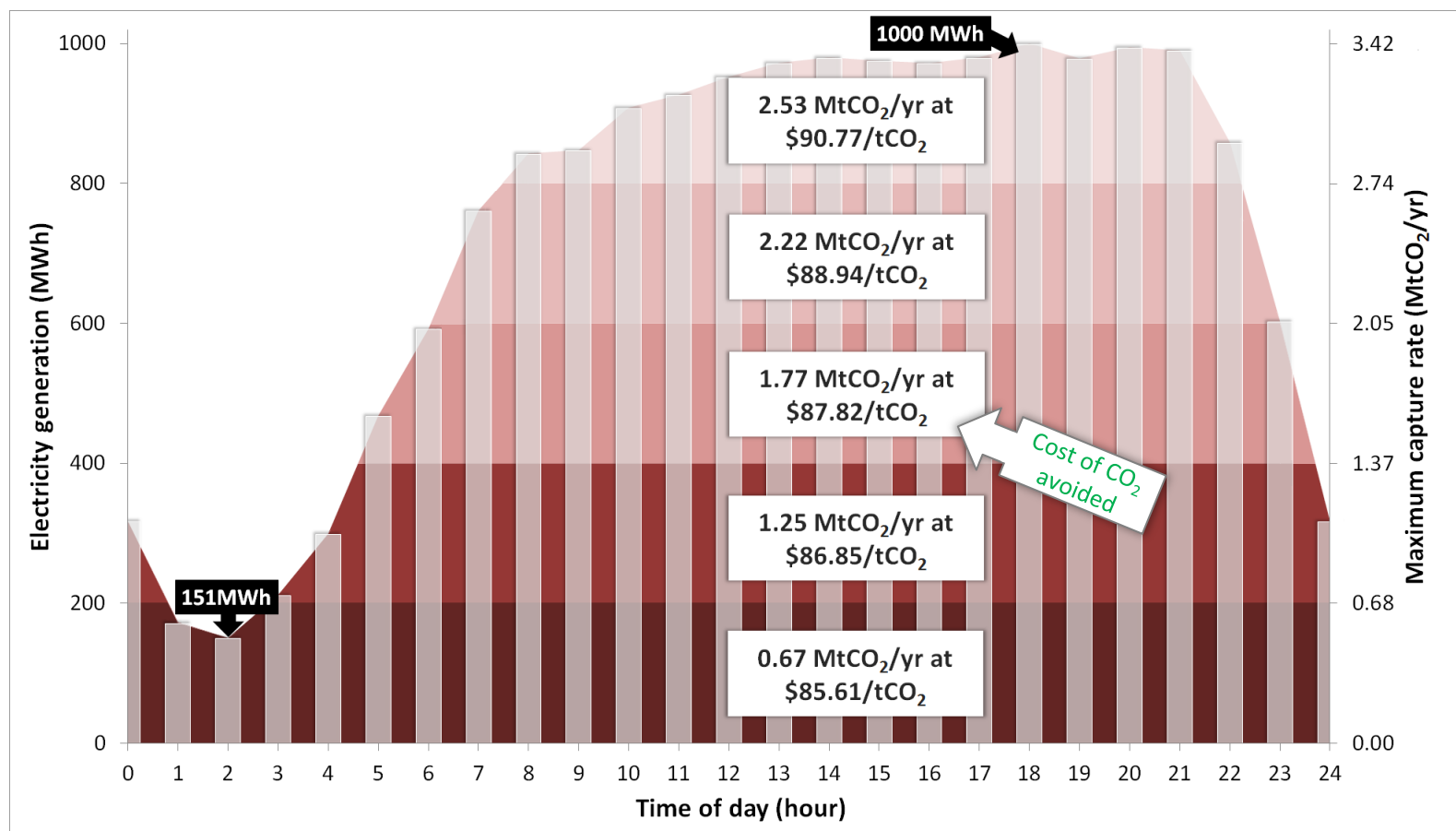
**Capture**

**Variability**

Boilers

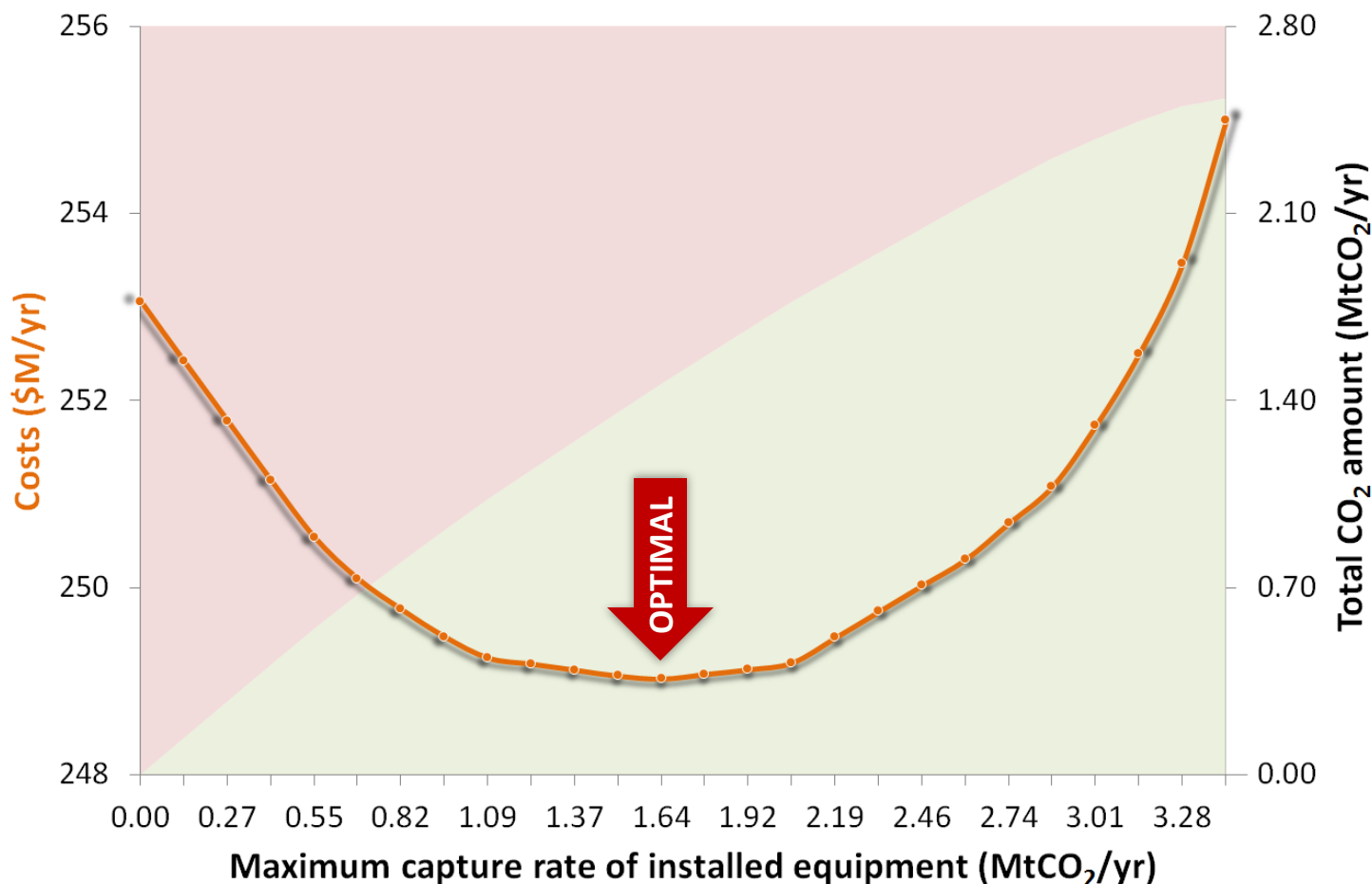
Cost

La Fin



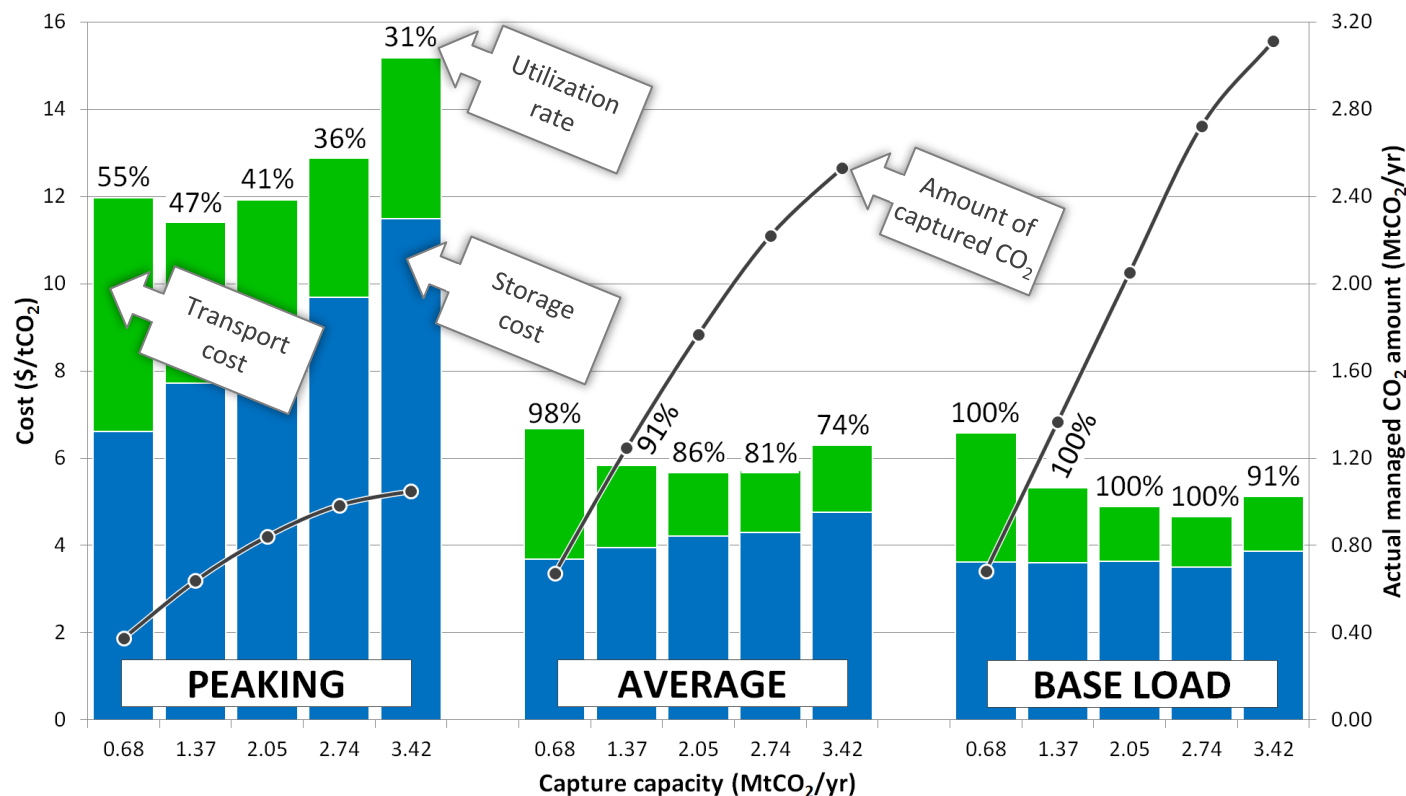
## Cost of CO<sub>2</sub> avoided

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



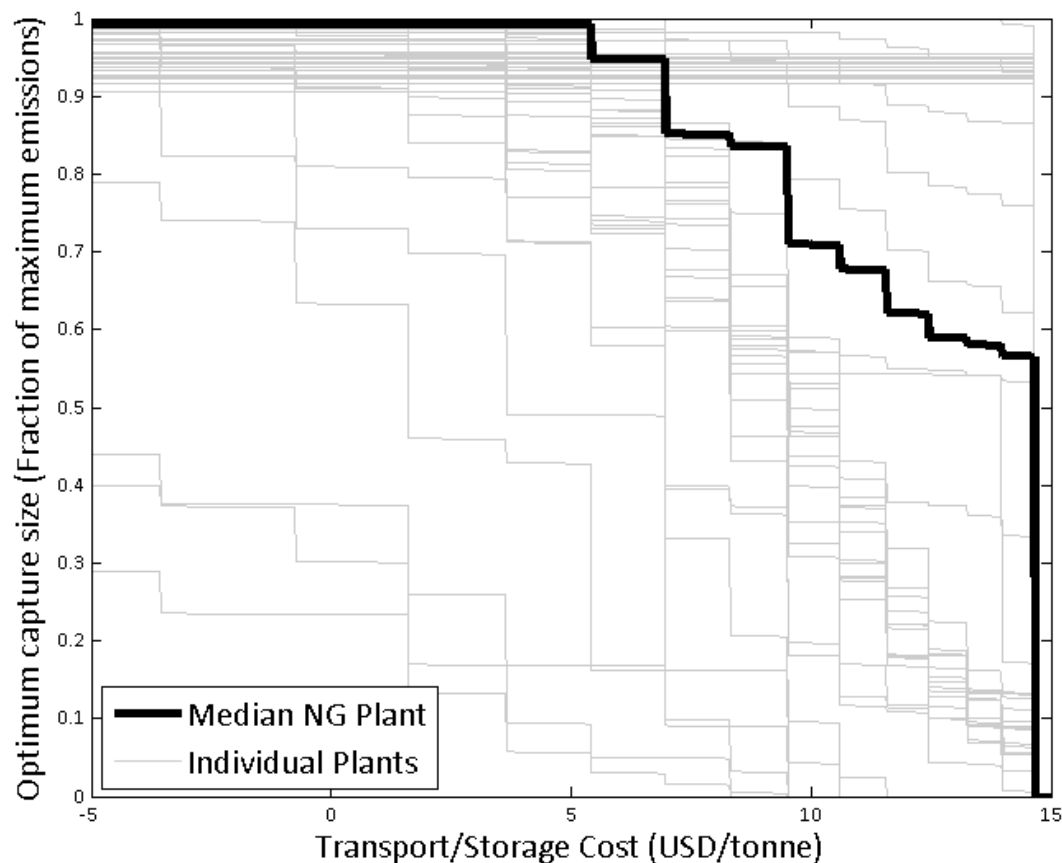
## Efficiency of transport and storage

- variable electricity = variable CO<sub>2</sub> rate throughout each day
- **transport** & **storage** infrastructure utilization rates
- under-utilized infrastructure is much more costly
- onsite temporary storage



## CO<sub>2</sub> transport and storage

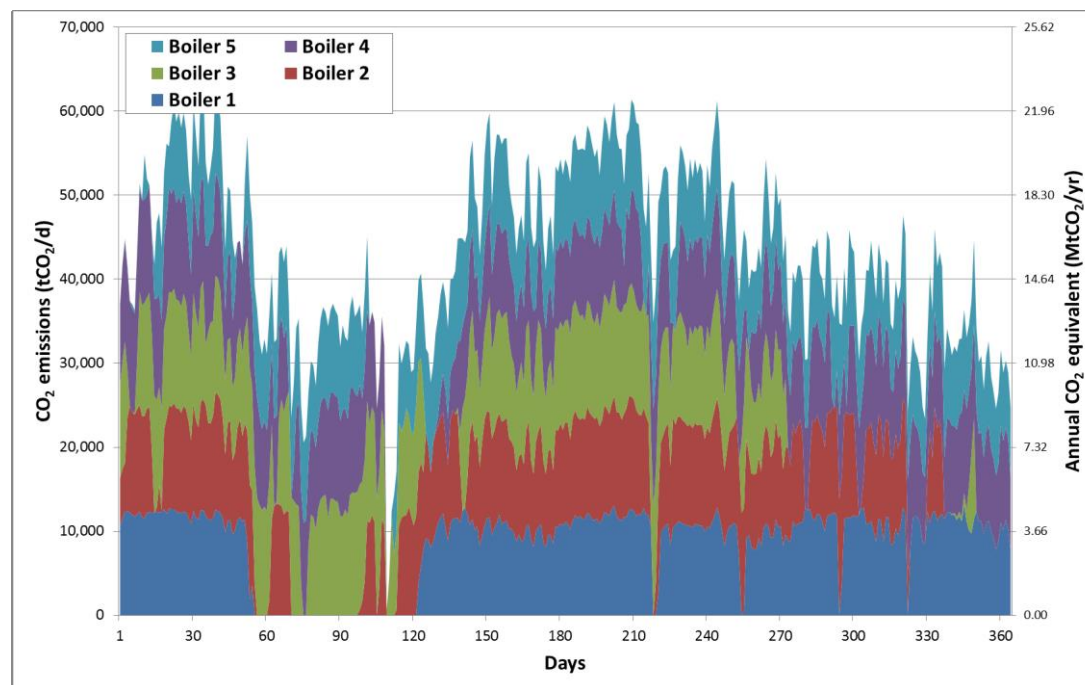
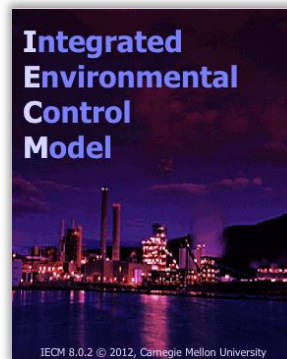
- often considered less important than capture, due to costs
- likely a critical factor for estimating CCS costs and policy
- should be considered endogenously





## Economics and engineering

- site-specific data for 1347 boilers (536 plants), including coal type, delivered-coal cost, heat rate, hourly CO<sub>2</sub> and electricity, etc.
- CO<sub>2</sub>/electricity from EPA's AMPD
- detailed economic and engineering for 400 coal-fired boilers using IECM



Gibson Generating Station, Indiana (2011)

## MENU

CCS

SimCCS

Case studies

Storage

Transport

**Capture**

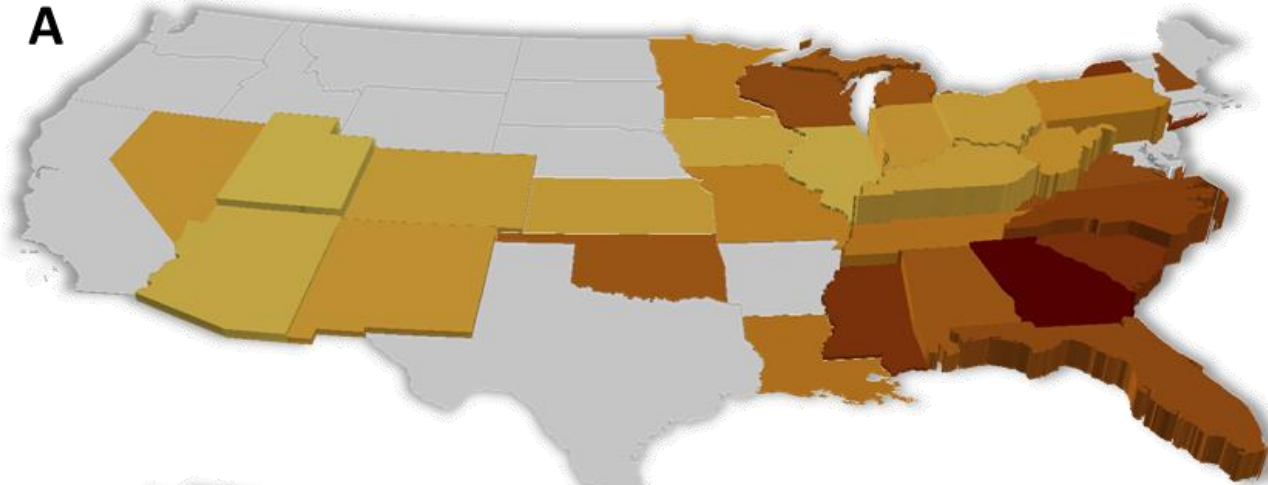
Variability

**Boilers**

Cost

La Fin

**A**



**B**

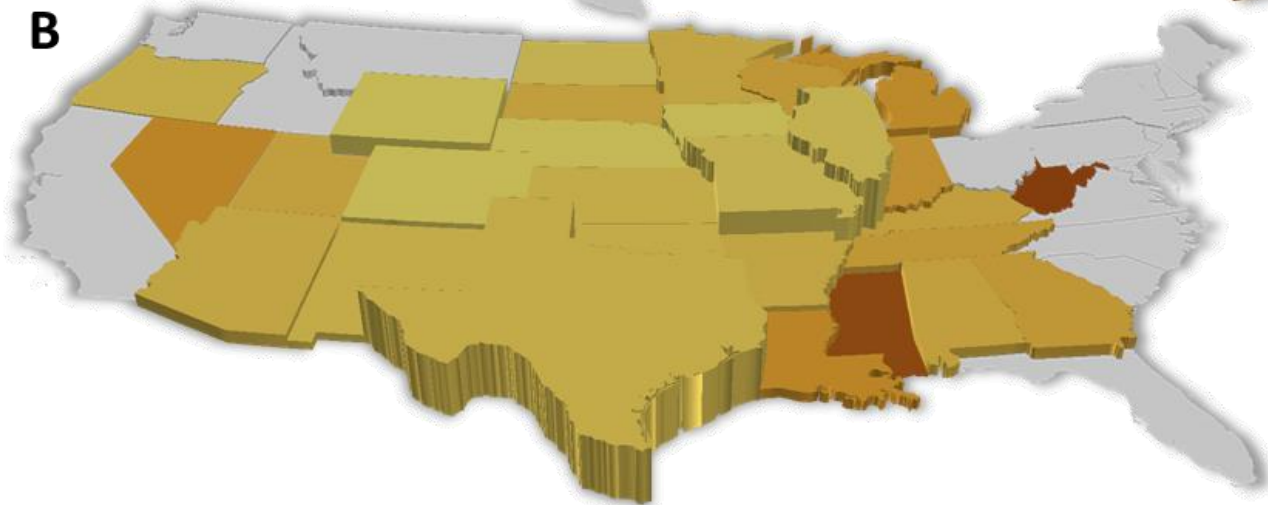
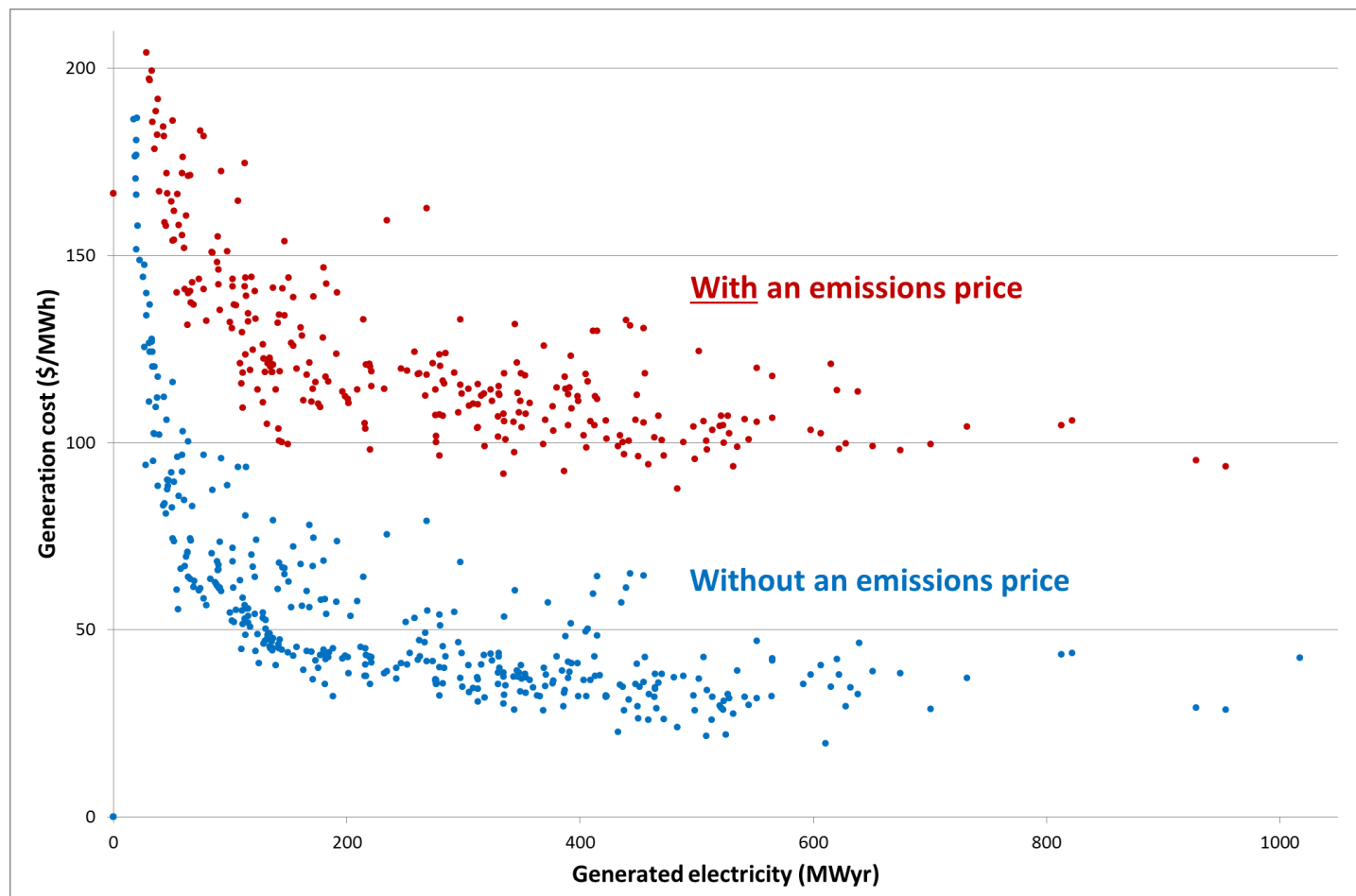


Figure 1: Cost (shading) and total heat (height) of delivered (A) bituminous and (B) sub-bituminous coal. Parts A and B use the same scales. Costs range from \$1.35/GJ (light shading—lowa) to \$4.34/GJ (dark shading—Georgia). States without sufficient reported costs in Form EIA923 are not shaded. Amount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

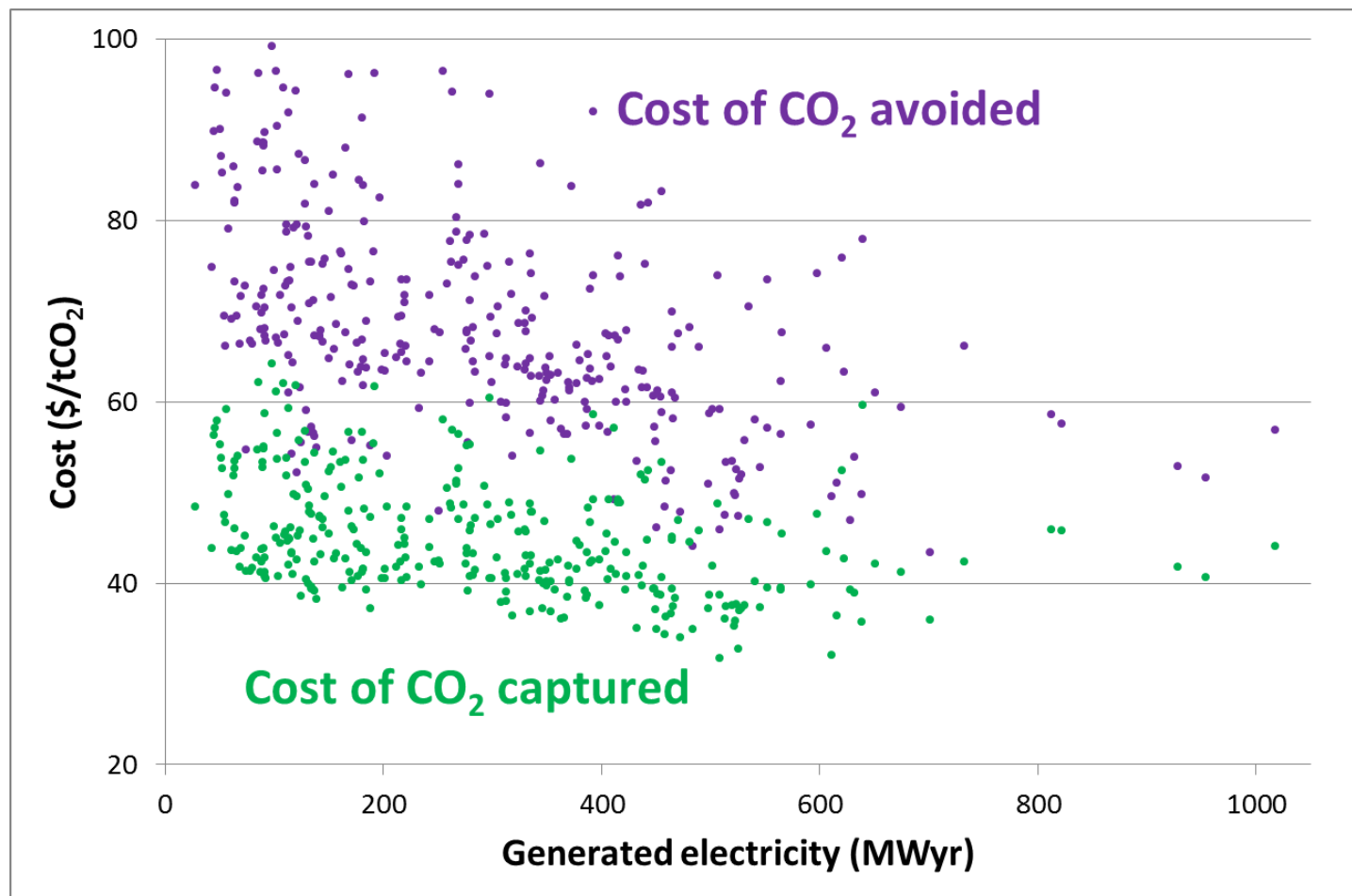
**Comparison:** post-retrofit electricity costs should be compared to pre-retrofit cost WITH CO<sub>2</sub> emissions price

**Chart:** CO<sub>2</sub> tax = \$75/tCO<sub>2</sub>



# CO<sub>2</sub> capture and avoided costs

- CO<sub>2</sub> emissions price = \$100/tCO<sub>2</sub>
- plants that do not capture CO<sub>2</sub> at this price are omitted
- marginal cost of CO<sub>2</sub> avoided dictates capture decision





# Impact of CO<sub>2</sub> emissions price

- vary emissions price from \$50-150/tCO<sub>2</sub>

## MENU

CCS

SimCCS

Case studies

Storage

Transport

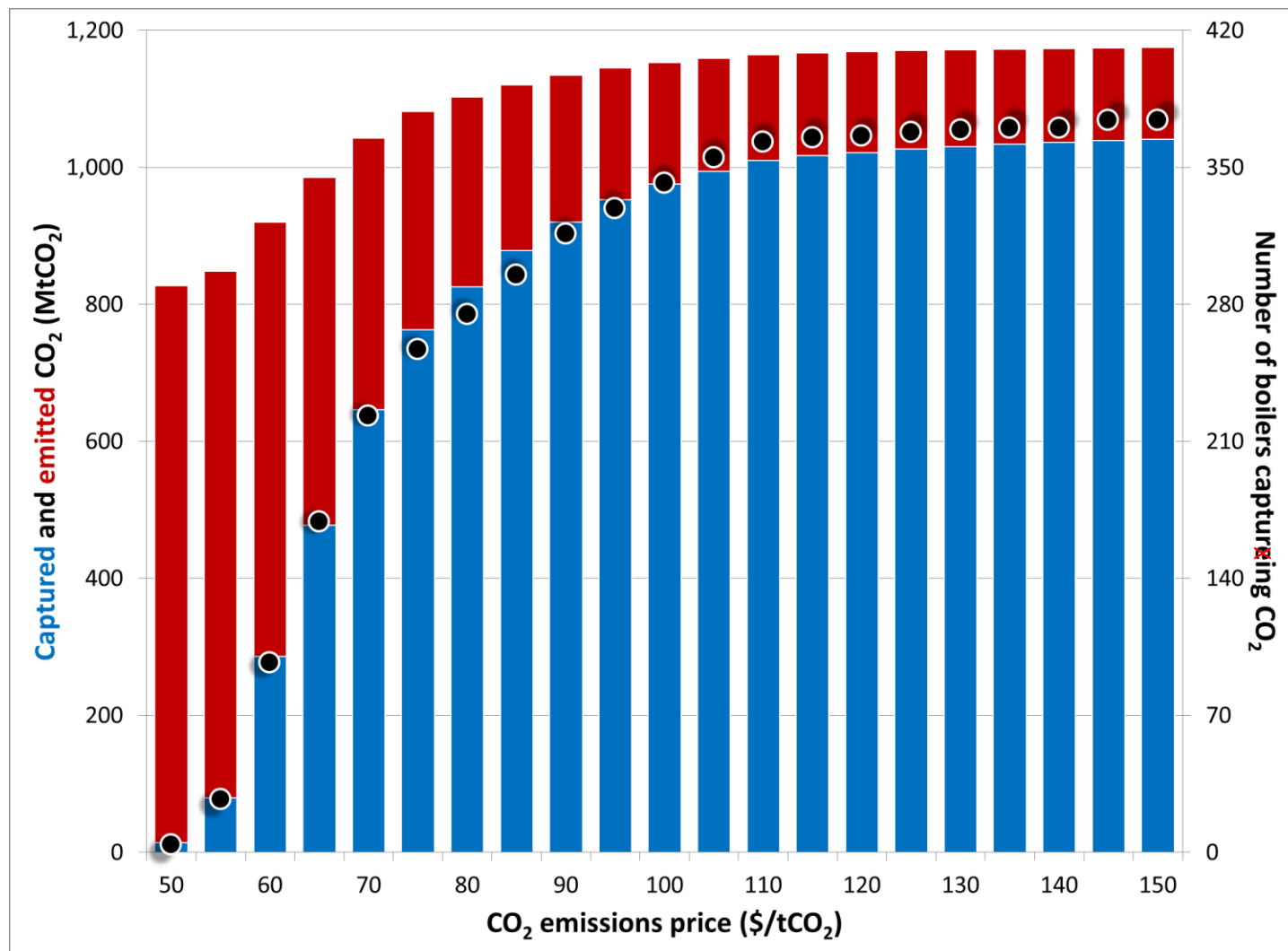
**Capture**

Variability

Boilers

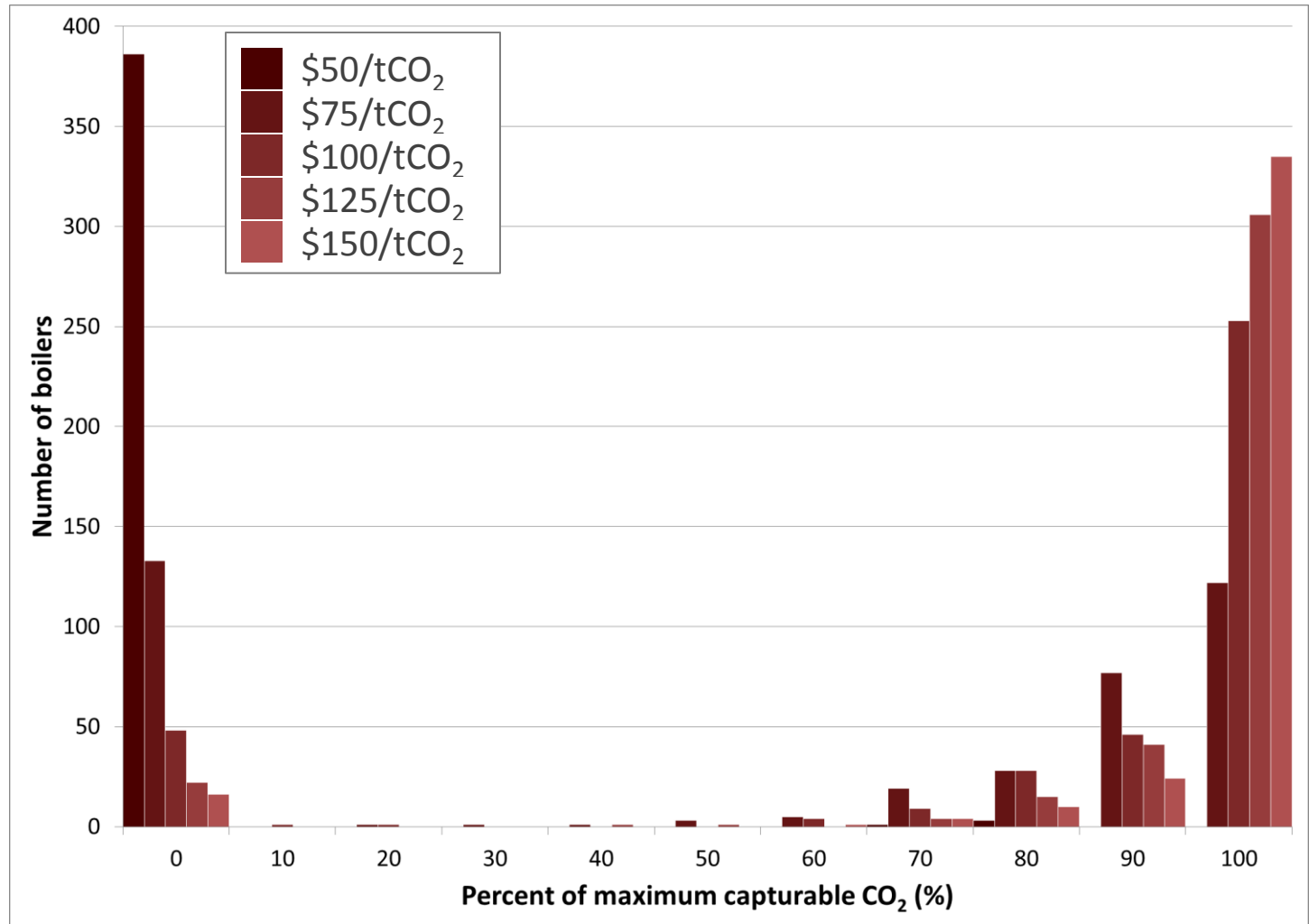
**Cost**

La Fin



# Response to a price on carbon

- tend to capture none or most/all of their capturable CO<sub>2</sub>
- relatively small variations in daily profile



## MENU

CCS

SimCCS

Case studies

Storage

Transport

**Capture**

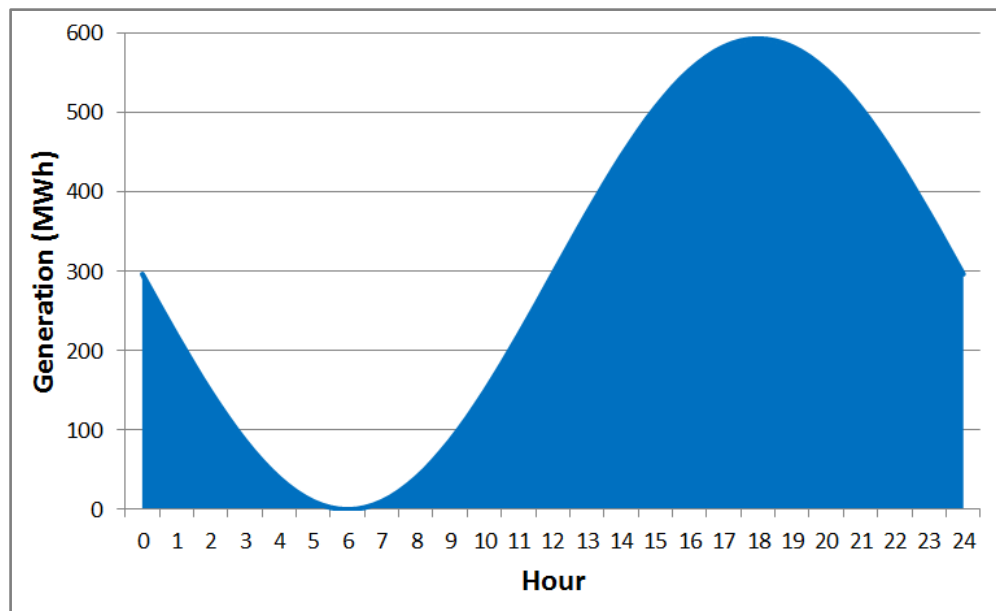
Variability

Boilers

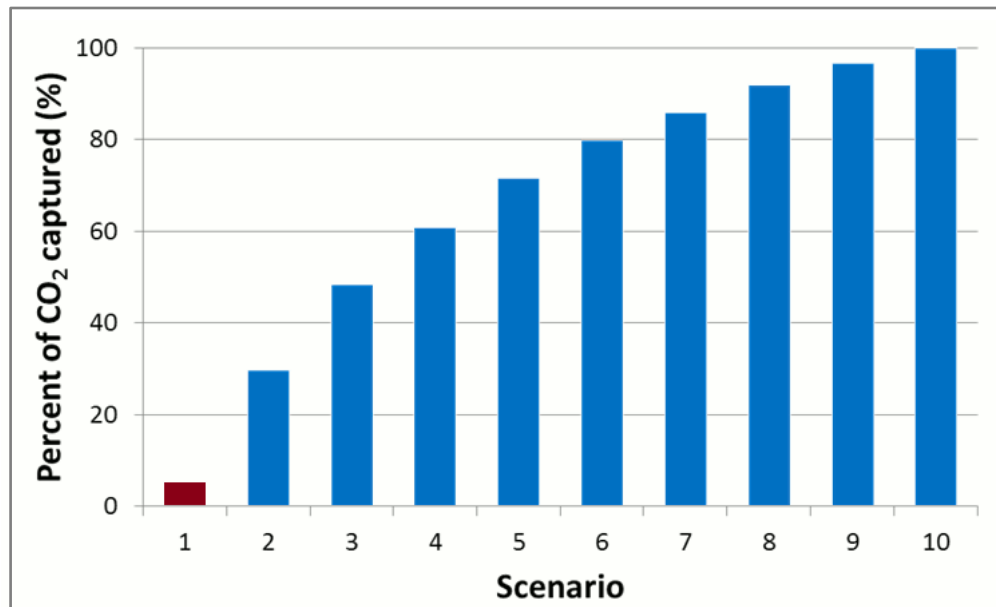
**Cost**

La Fin

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



- generation profile drives how much CO<sub>2</sub> the coal-fired plant will capture
- replicates capture performance of natural gas plants



## CCUS

- significant potential for CO<sub>2</sub> emissions reduction
- requires comprehensive understanding of CO<sub>2</sub> 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.

### MENU

CCS

SimCCS

Case studies

Storage

Transport

Capture

La Fin

Take home