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

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Abstract

Carbon capture, utilization, and storage (CCUS) is a key mitigation technology capable of reducing CO_2 emissions on an industrial scale without requiring a fundamental restructuring of energy systems. To have a meaningful impact, CCUS will need broad implementation that requires power utilities to develop comprehensive business plans integrating electricity production, CO_2 capture, CO_2 transport, utilization revenue, and CO_2 storage issues. Developing such business plans is a significant challenge, and CCUS has thus far had a very limited impact in mitigating CO_2 emissions (~40 million tonnes of CO_2 mitigated in 2014 versus global emissions estimated around 40 billion metric tons). In this paper, a first-of-a-kind framework termed SimCCUS is introduced that integrates key CCUS science, engineering, and economic concerns, allowing stakeholders to assess the feasibility and business impact of distinct business plans. Specifically, the framework has the novel capability to evaluate four separate business-model strategies, ranging from full vertical integration (e.g., power utility and subsidiaries are responsible for capture, transport, utilization, and storage of CO_2) to pay-at-the-gate models (utility pays a third party to handle emissions from the power plant site). SimCCUS integrates geological models of CO_2 utilization and storage in stacked reservoir systems (deep saline formations underlying utilization options for enhanced oil recovery, enhanced coal-bed methane production, and enhanced gas recovery) with engineering and economic parameters to design optimal CCUS infrastructure networks that allow stakeholders to assess which, if any, CCUS business model is most feasible. Using a case study of a representative coal-fired power plant in the Illinois Basin (USA) we illustrate how the feasibility of different business models varies with market (e.g., oil

price) and regulatory (e.g., CO_2 emissions price) conditions, as well as desired CO_2 capture and electricity-generation rates. The framework shows how, where, and when CCUS infrastructure should be constructed, including propensity for utilization options to be deployed early in the project lifecycle, followed by stacked saline formation storage that leverages existing surface infrastructure. Given the further advantage of facilitating connections between power utilities and businesses interested in CO_2 utilization, it is hoped that SimCCUS could be a key tool for jumpstarting CCUS in the near future.

Reference Cited

Global CCS Institute 2014, The Global Status of CCS: 2014, Melbourne, Australia, 188 p.

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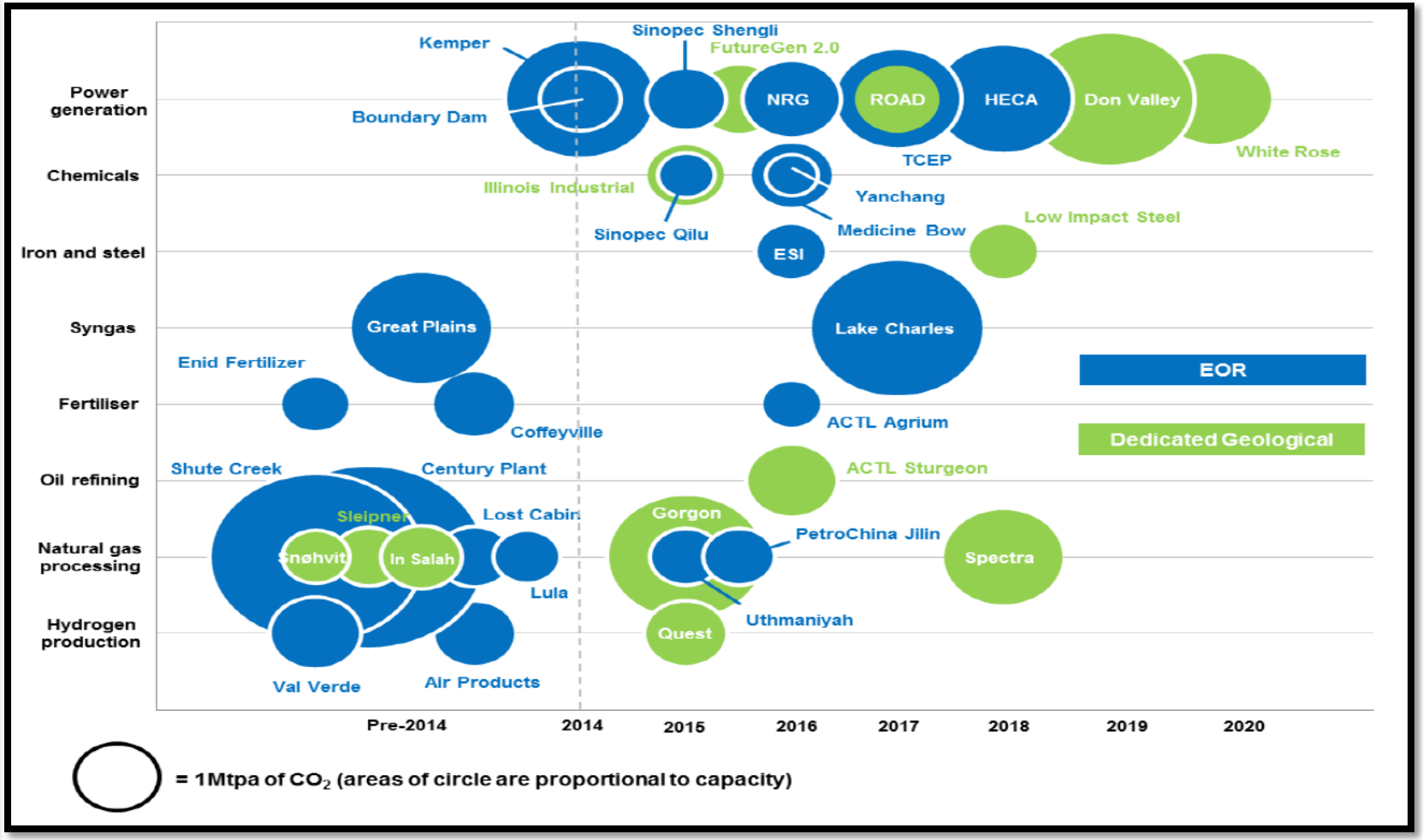
MENU

Issue: Despite significant, global R&D effort, CCUS technology is mitigating < 0.1% of global CO_2 emissions



Source: Global CCS Institute, 2014

Objective: Develop new decision support tool for CCUS

DESCRIPTION

- coupled *economic-engineering* decision-making framework for CCS *scientists*, *stakeholders*, and *policy makers*
- understand how CCS technology—capture, transport, storage—could and should be deployed on an *industrial scale*
  - ***SimCCUS^{CAP}***: *cap-and-trade environment*
  - ***SimCCUS^{PRICE}***: *CO_2 tax*
  - ***SimCCUS^{TIME}***: *infrastructure evolution*

OPTIMIZATION ENGINE

$$\underbrace{\sum_{i\in S}(c_i^s u_i)}_{\text{Cost to open source, capture } CO_2} + \underbrace{\sum_{i\in I}\sum_{j\in N_i}\sum_{d\in D}(c_{ijd}^p y_{ijd} + c_{ij}^r x_{ij})}_{\text{Cost to purchase land, construct pipeline, and transport } CO_2} + \underbrace{\sum_{j\in R}(c_j^r b_j)}_{\text{Cost to open reservoir, inject } CO_2}$$

(1)	$x_{ij} - \sum_{d\in D} \max Q_{ijd}^p y_{ijd} \le 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be less than maximum pipeline capacity
(2)	$x_{ij} - \sum_{d\in D} \min Q_{ijd}^p y_{ijd} \ge 0$	$\forall i \in I, j \in N_i$	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)	$a_i - Q_i^s s_i \le 0$	$\forall i \in S$	CO_2 captured at a source must not exceed supply
(5)	$b_j - Q_j^r r_j \le 0$	$\forall j \in R$	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

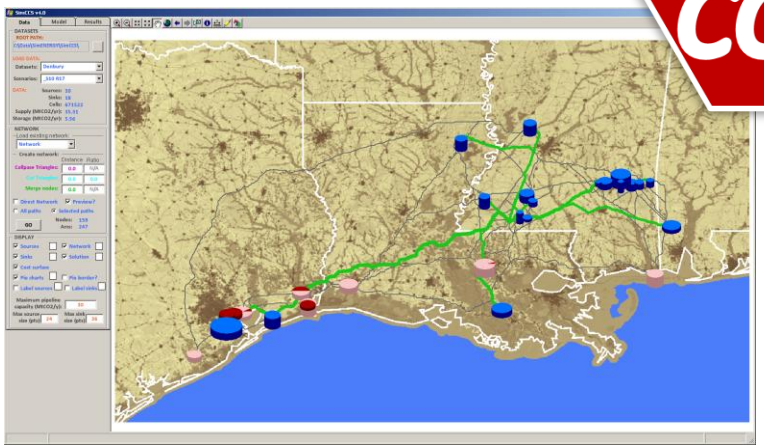
$y_{ijd} \in \{0,1\}$ $\forall i \in I, j \in N_i, d \in D$
$s_i \in \{0,1\}$ $\forall i \in S$
$r_j \in \{0,1\}$ $\forall j \in R$

0,1 constraints

$x_{ij} \ge 0$ $\forall i, j \in N_i$
$a_i \ge 0$ $\forall j \in S$
$b_j \ge 0$ $\forall j \in R$

Non-negativity constraints

INTERFACE

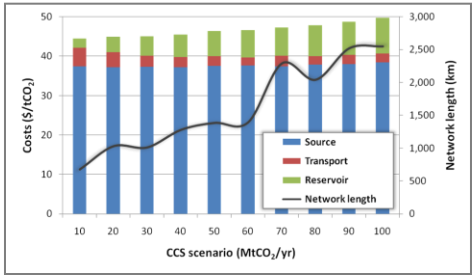


- custom/open-source GIS, network generation, model building

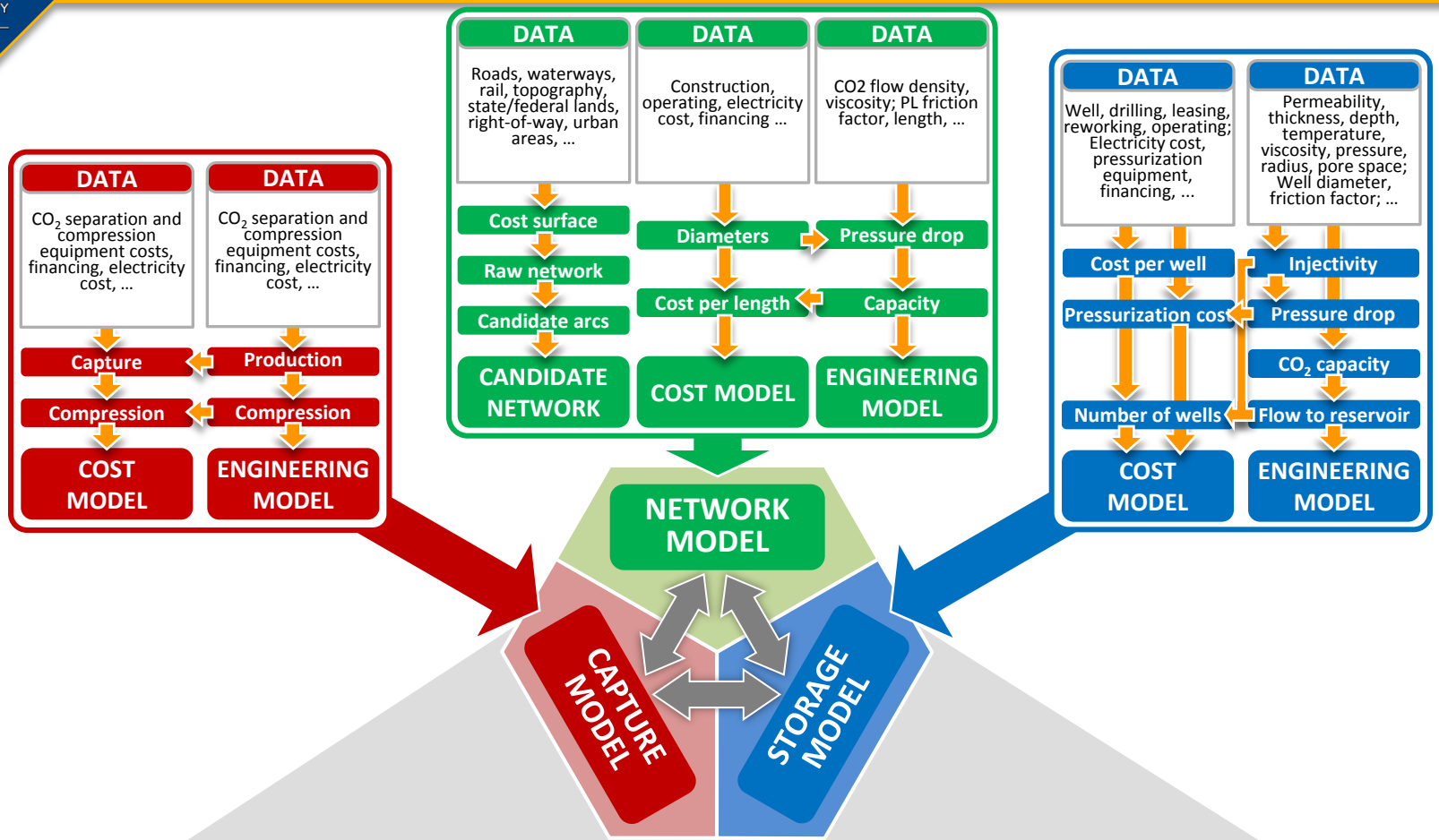
POLICY ANALYSIS

Spatial analysis

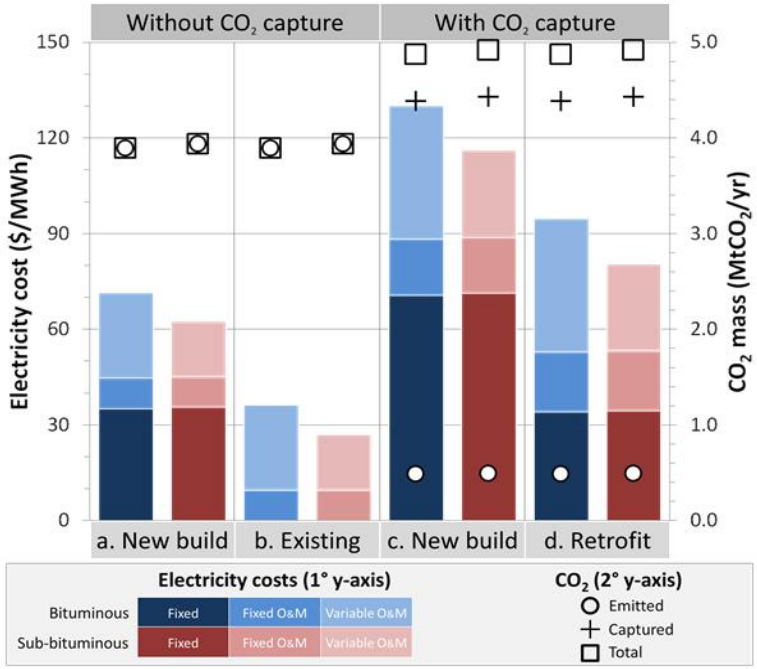
Economics & engineering

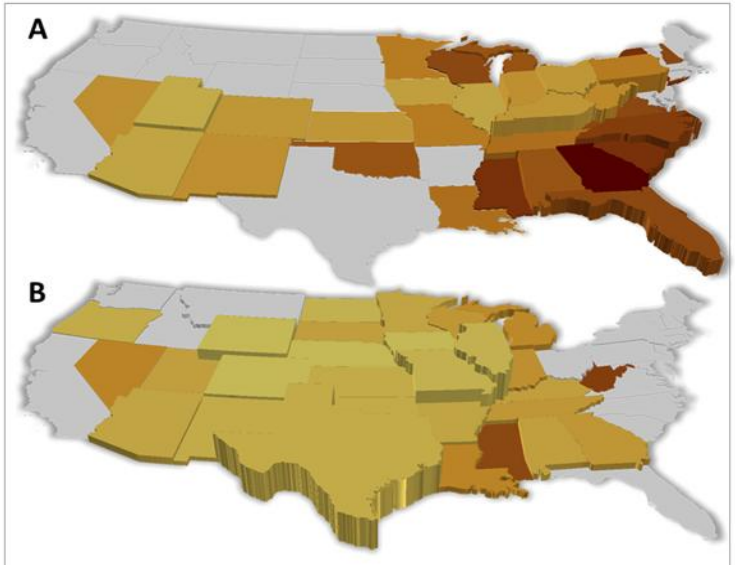


SimCCUS: Scalable Infrastructure Model for CCUS

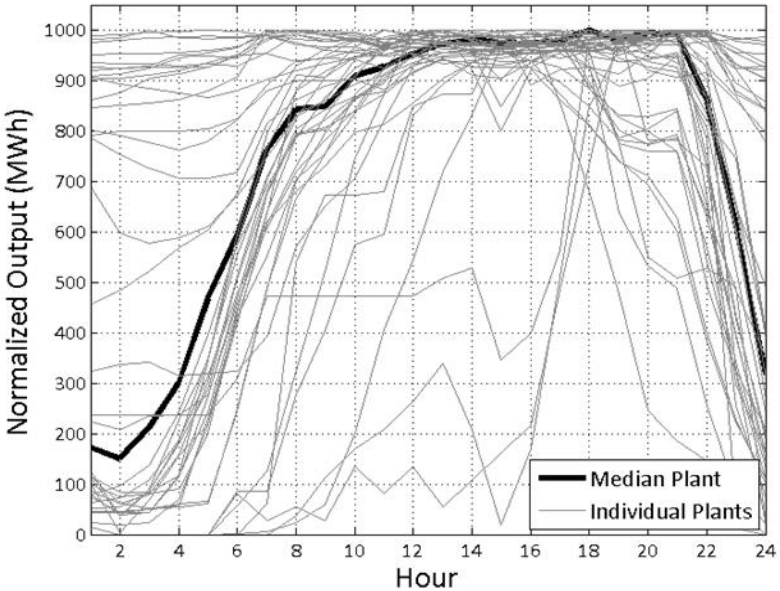


COSTS	SPATIAL DEPLOYMENT	CO_2 FLOWS	GENERAL
Cost to deploy CCS infrastructure	**Where to capture and/or release CO_2**	**CO_2 amount to be captured at each source**	Amount of CO_2 cost-effectively sequestered
Capture, transport, and storage costs	Location of capture-ready CO_2 sources	**How much CO_2 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

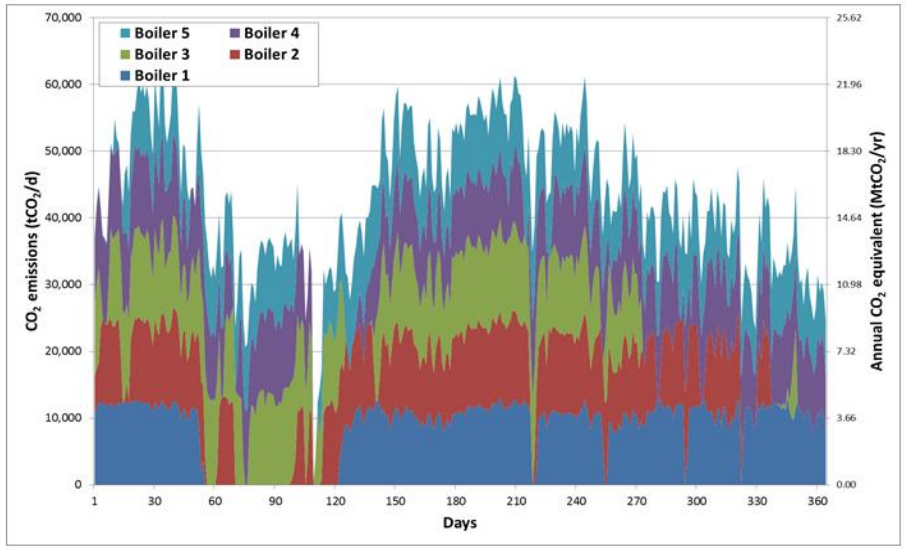




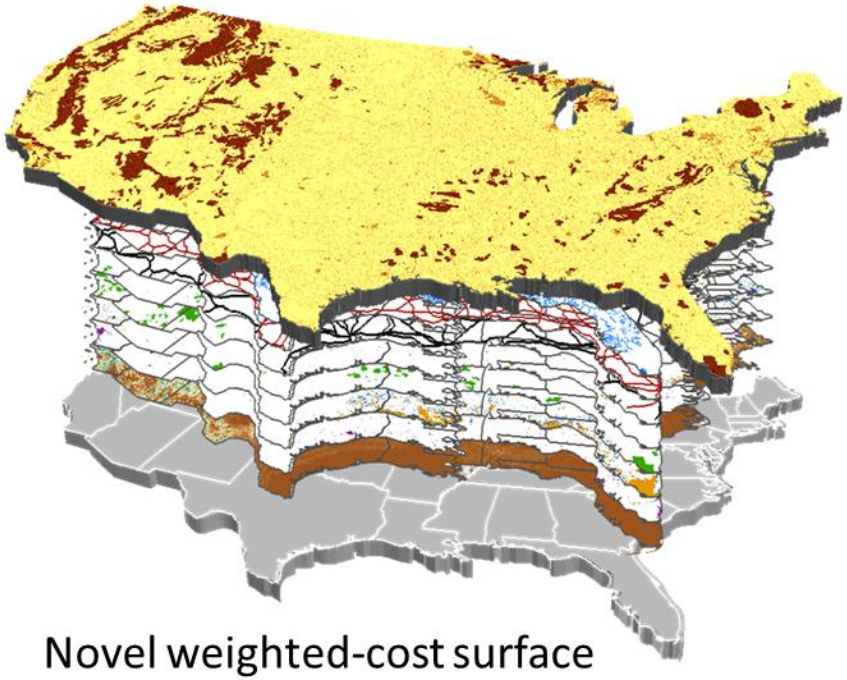
Full cost of bituminous (A) and sub-bituminous (B)coal



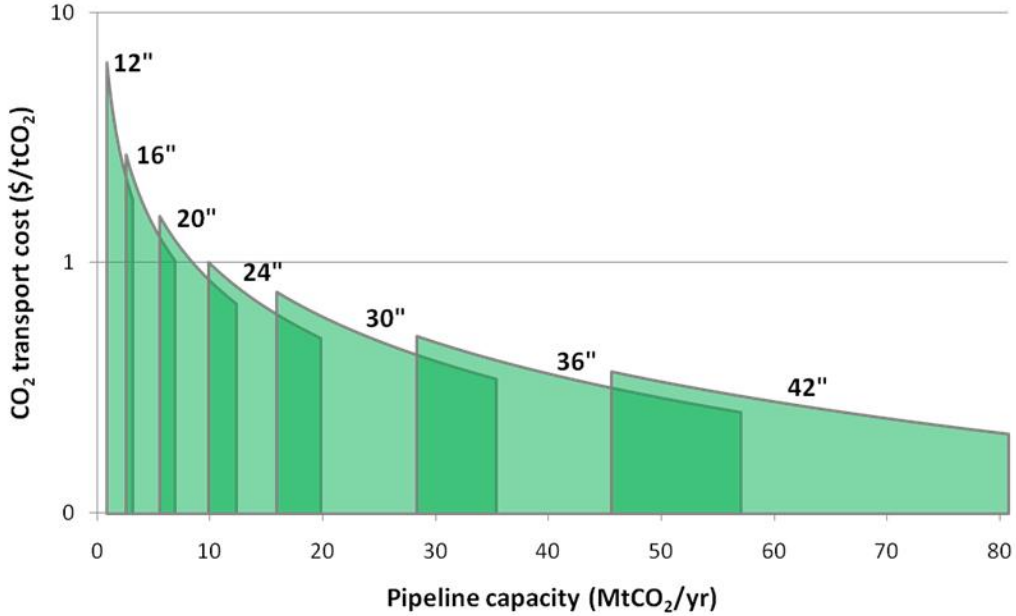
Impact on electricity generation costs



Boiler-level generation and emissions

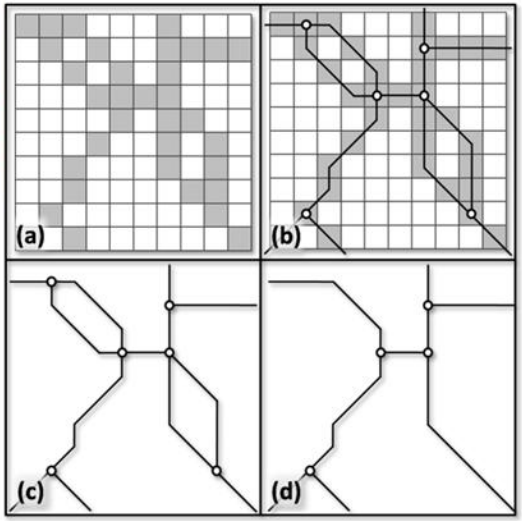


Novel weighted-cost surface

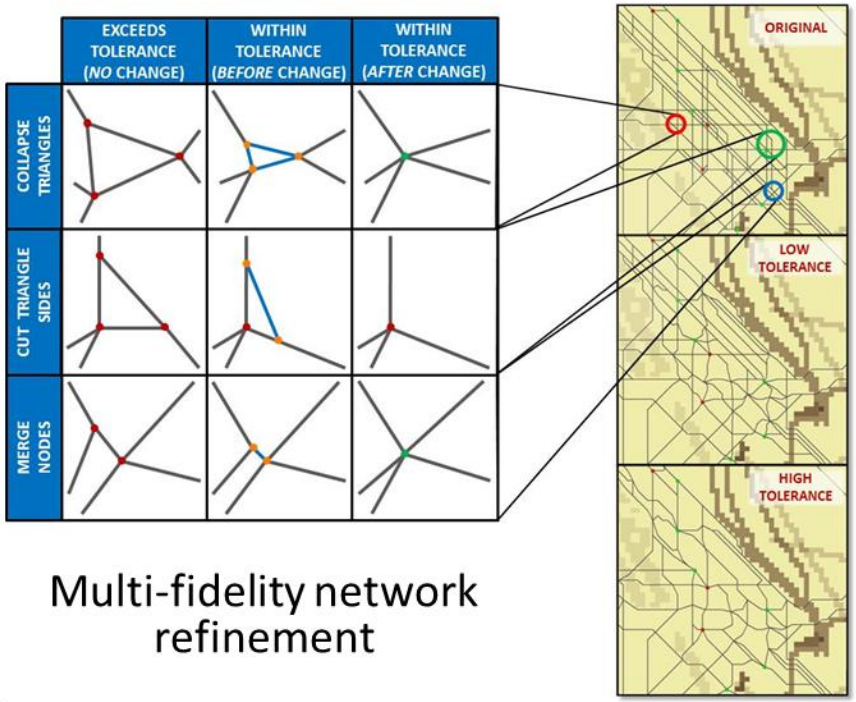


Pipeline economies of scale

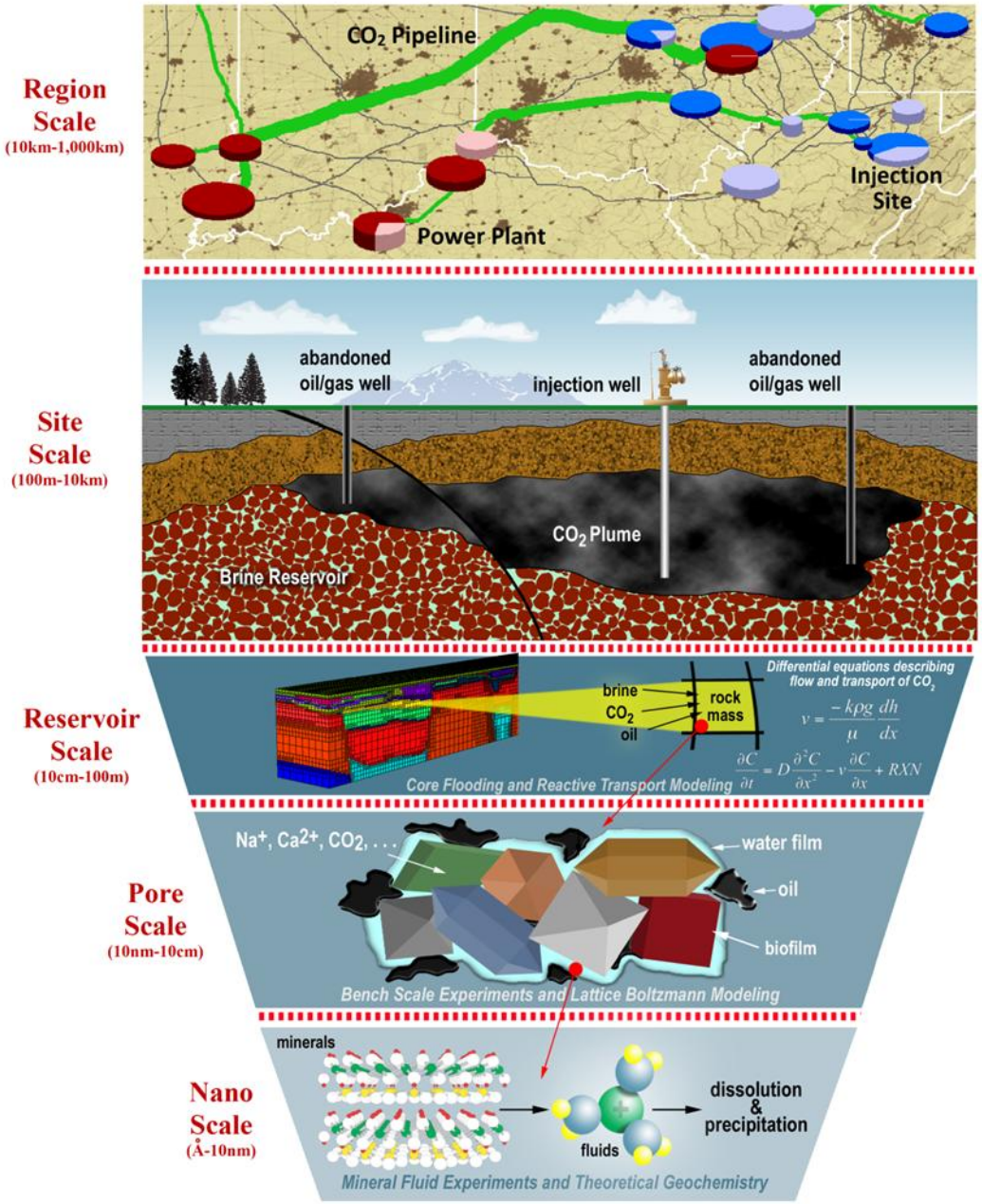
Discrete path analysis

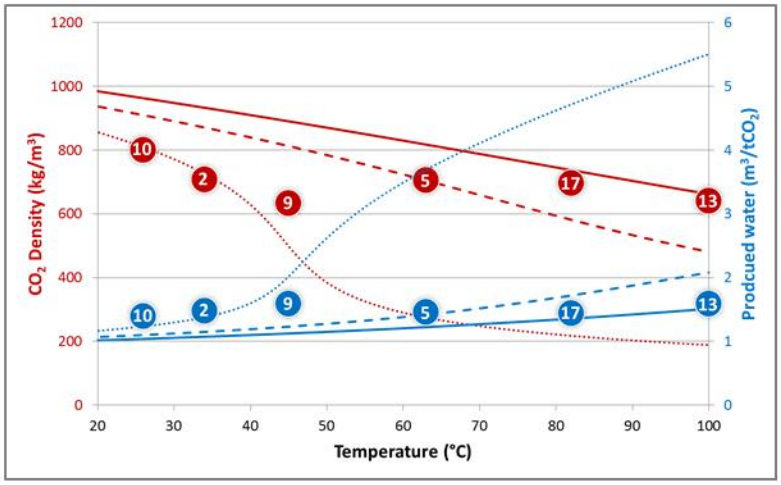


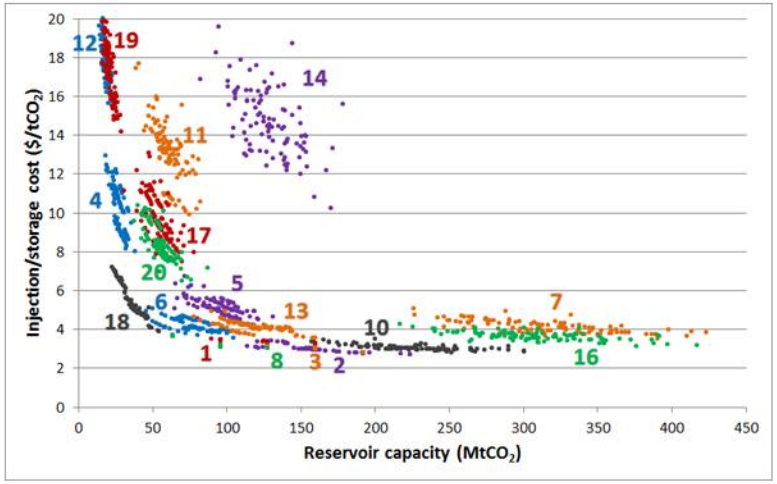
(a) Raster paths
(b) Identify nodes
(c) Network with duplicates
(d) Raw candidate network

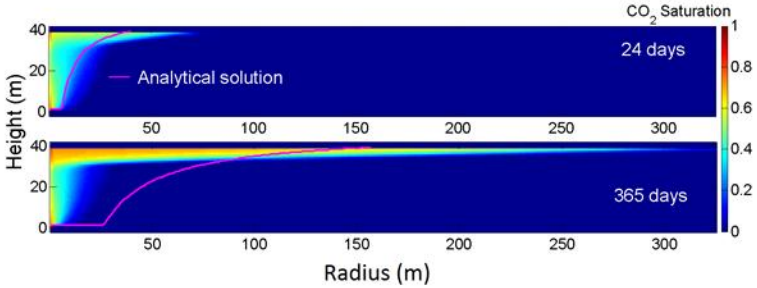


Multi-fidelity network refinement


Region Scale
(10km-1,000km)
CO2 Pipeline
Injection Site
Power Plant
Site Scale
(100m-10km)
abandoned oil/gas well
injection well
abandoned oil/gas well
CO2 Plume
Brine Reservoir
Reservoir Scale
(10cm-100m)
brine
CO2
oil
rock mass
Differential equations describing flow and transport of CO2
Core Flooding and Reactive Transport Modeling
Pore Scale
(10nm-10cm)
Na+, Ca2+, CO2, . . .
water film
oil
biofilm
Bench Scale Experiments and Lattice Boltzmann Modeling
Nano Scale
(Å-10nm)
minerals
fluids
dissolution & precipitation
Mineral Fluid Experiments and Theoretical Geochemistry

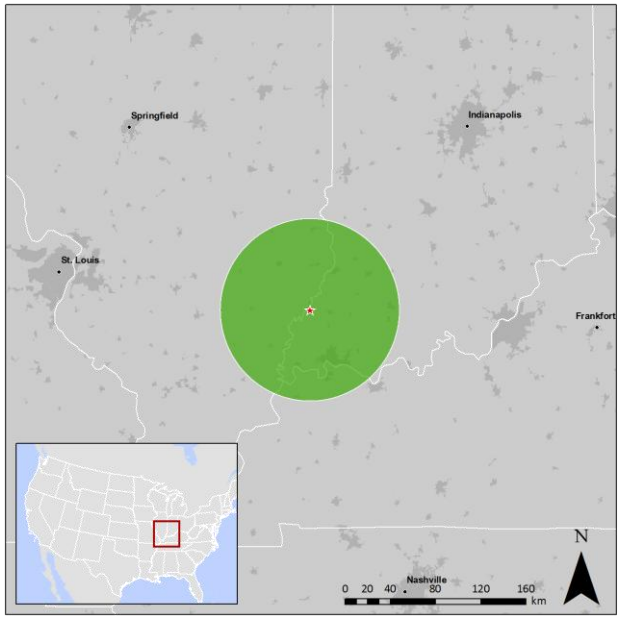

CO2 Density (kg/m3)
Prodcued water (m3/tCO2)
Temperature (°C)


Injection/storage cost ($/tCO2)
Reservoir capacity (MtCO2)


CO2 Saturation
24 days
Analytical solution
365 days
Height (m)
Radius (m)

Case study: Gibson Generating Station

- Emissions: Up to 15 $MtCO_2$/yr
- Capture cost: \$65/tCO_2
- 15 coupled storage-utilization sites
- Stacked storage: saline & utilization
- First order CO_2 utilization values
  - EOR: \$40/tCO_2
  - ECBM: \$5/tCO_2
  - Shale gas: \$10/tCO_2



Node	location	utmX	utmY	SF-MTSMN	SF-KNOX	SF-STPTR	EOR/O&G	ECBM/UC	EGR/NAS
1	On site at Gibson Station	433093	4247026	10	6	26	10	0.4	
2	Clay, IL	384900	4276700	13	6	26	109	1	
3	Tri County	454500	4306500	9	8	54	2	0.2	
4	Lawrence, IL	435800	4283800	10	7	45	48	1	
5	Crawford, IL	432700	4310500	9	8	37	64	0.5	
6	White, IL	410400	4225000	12	5	23	51	1	
7	Pike, IN	463000	4258500	9	7	35	15		
8	Knox, IN	473500	4298500	8	7	43			62
9	Sullivan, IN	460600	4318900	8	8	45		0.25	47
10	Clay-Sailor, IL	378900	4295500	12	6	23	18	1	
11	Wabash, IL	422600	4248700	11	6	26	43	1	
12	Hamilton, IL	365800	4209500	18	5	21	28	0.4	
13	Posey, IN	418500	4214000	11	5	32	3	0.5	
14	Henderson, KY	440600	4168800	13	5	45	12	0.25	
15	Davies, KY	476600	4182500	12	5	51	2		

Color codes: relative resource level-- high resource | med resource | low resource

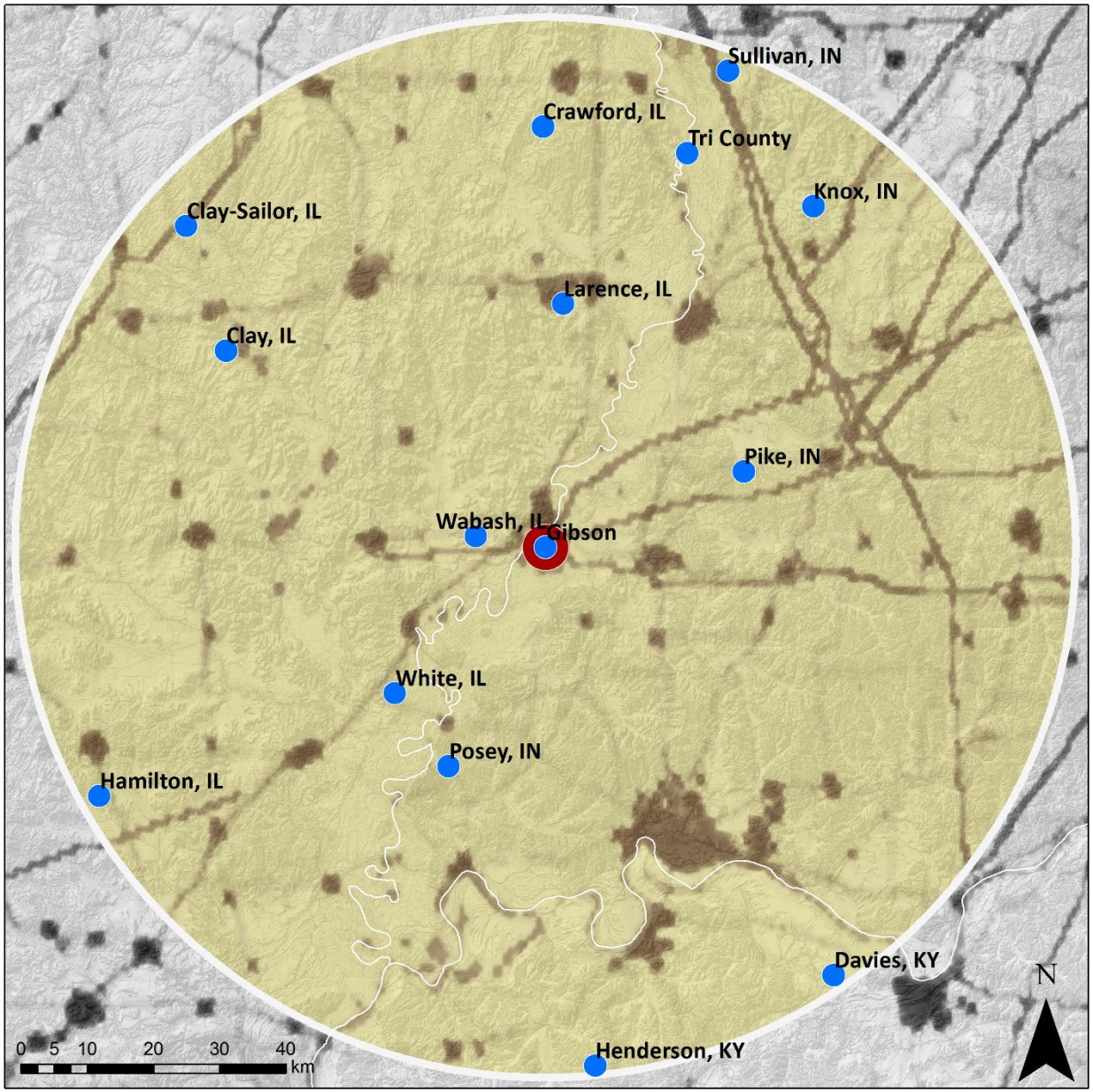
Overview: CO_2 source and reservoirs

Sinks

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

Cost surface

- Based on geographical features (e.g., slope, ROWs, land ownership, trans-mission lines, roads, rivers, etc.) → potential pipe-line routes



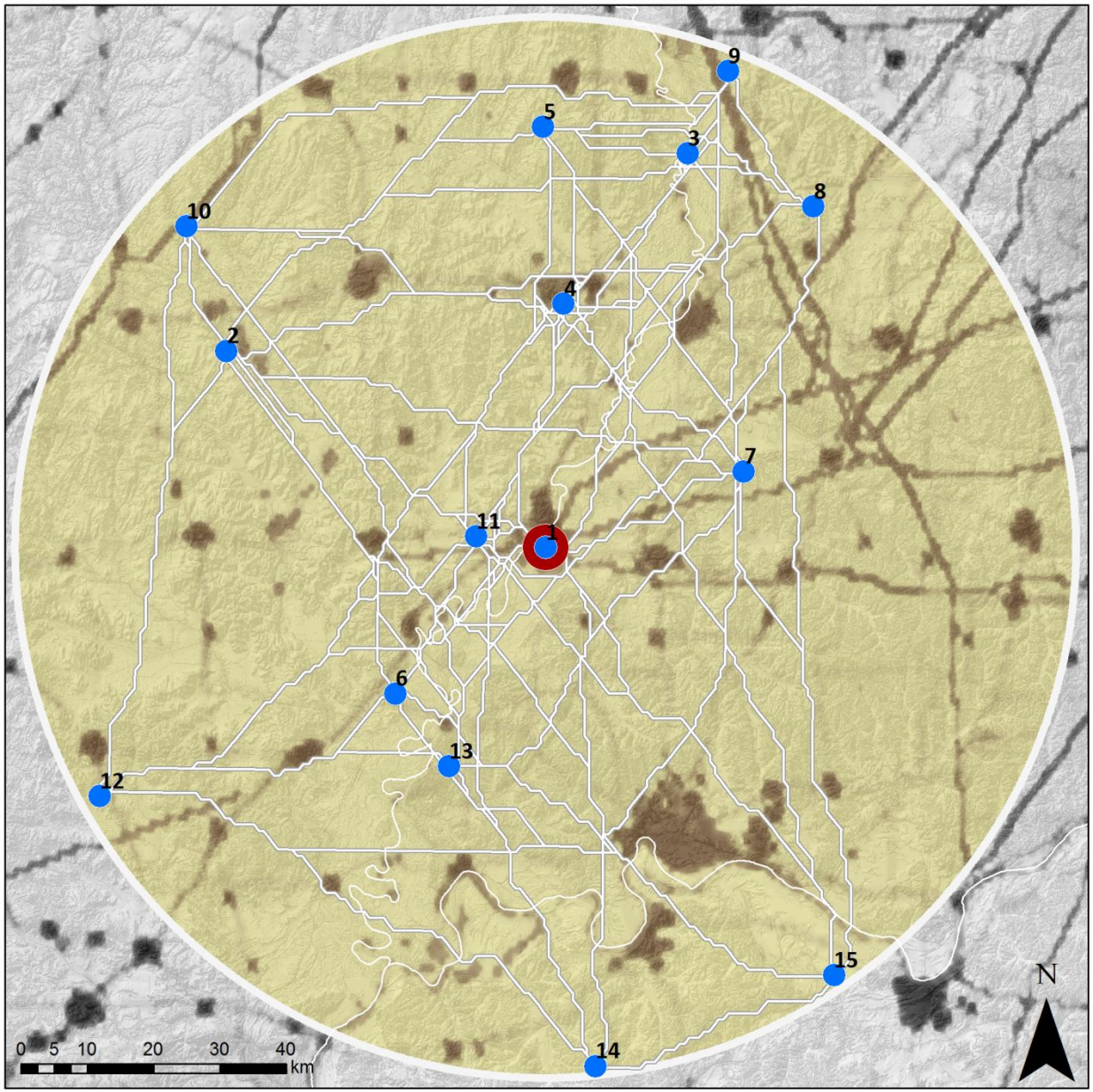
Overview: candidate pipeline network

Sinks

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

Cost surface

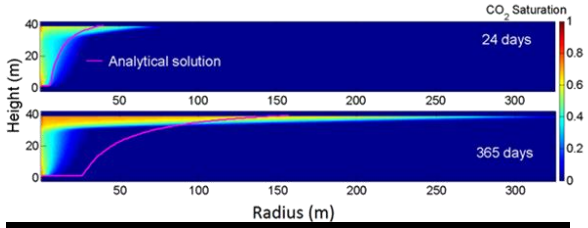
- Based on geographical features (e.g., slope, ROWs, land ownership, trans-mission lines, roads, rivers, etc.) → potential pipe-line routes

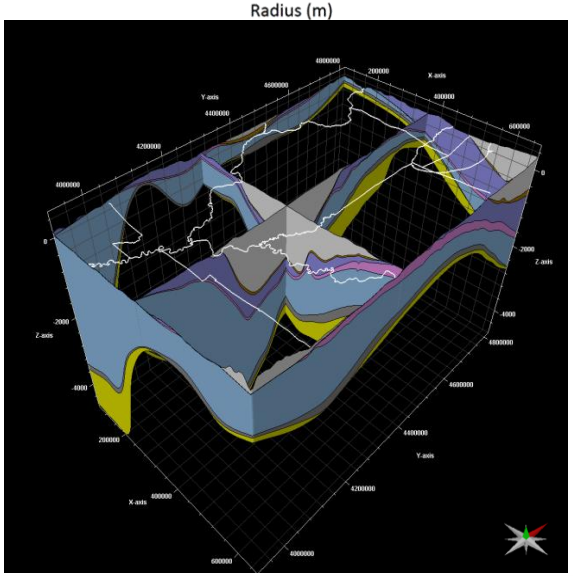


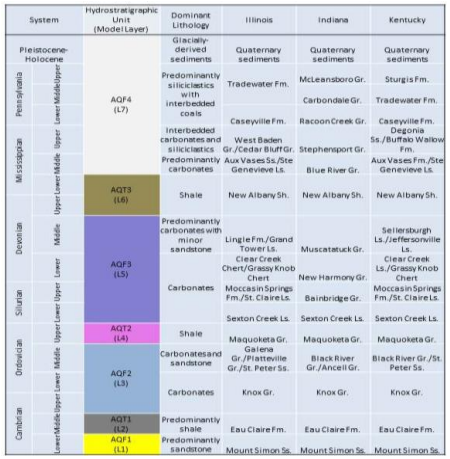
MENU
SimCCS
Case study
Storage
Saline
EOR
ECBM
Shale gas
Results
Future work
Conclusions

Stacked saline formations

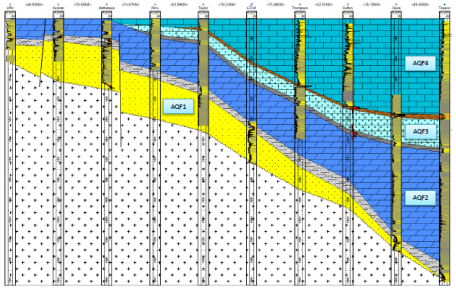
- Knox, Mt. Simon, and St. Peter
- Storage costs driven by: injectivity, plume radius, depth, water production & treatment, storage capacity, distribution pipelines…

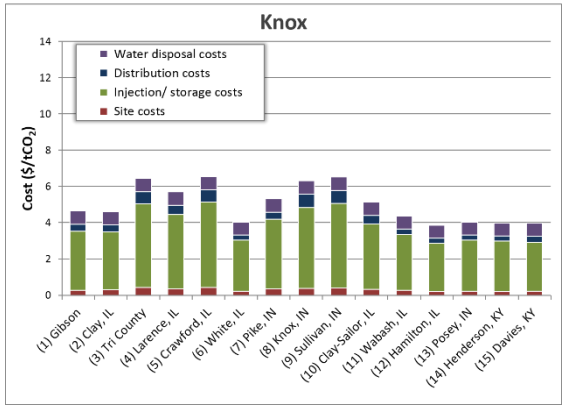


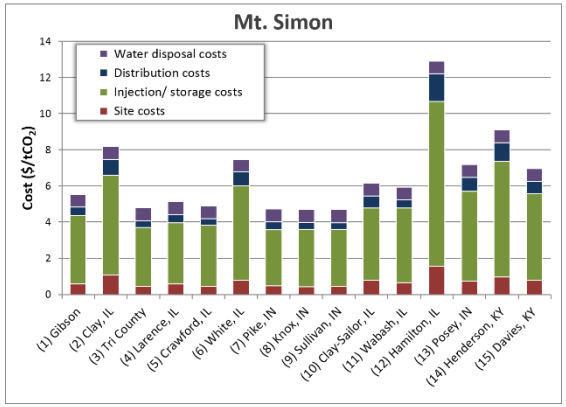


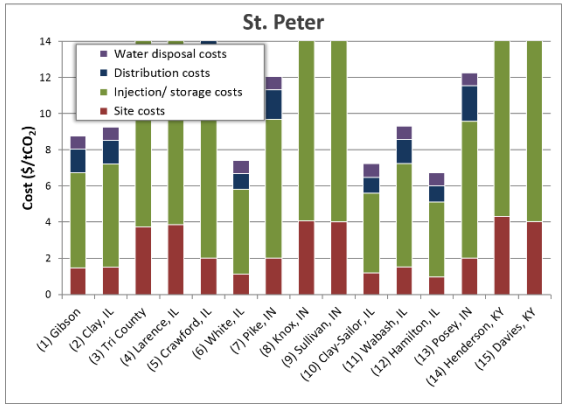


System	Hydrostratigraphic Unit (Model Layer)	Dominant Lithology	Illinois	Indiana	Kentucky
Pleistocene-Holocene		Glacially-derived sediments	Quaternary sediments	Quaternary sediments	Quaternary sediments
Pennsylvania	AQF4 (L7)	Predominantly siliciclastics with interbedded coals	Tradewater Fm.	McLeansboro Gr.	Sturgis Fm.
				Carbondale Gr.	Tradewater Fm.
Mississippian		Interbedded carbonates and siliciclastics	Caseyville Fm.	Racoon Creek Gr.	Caseyville Fm. Degonia Ss./Buffalo Wallow Fm.
		Predominantly carbonates	West Baden Gr./Cedar Bluff Gr. Aux Vases Ss./Ste Genevieve Ls.	Stephensport Gr.	Aux Vases Fm./Ste Genevieve Ls.
				Blue River Gr.	
	AQT3 (L6)	Shale	New Albany Sh.	New Albany Sh.	New Albany Sh.
Devonian	AQF3 (L5)	Predominantly carbonates with minor sandstone	Lingle Fm./Grand Tower Ls. Clear Creek Chert/Grassy Knob Chert	Muscatatuck Gr.	Sellersburgh Ls./Jeffersonville Ls. Clear Creek Ls./Grassy Knob Chert
		Carbonates	Moccasin Springs Fm./St. Claire Ls.	New Harmony Gr.	Moccasin Springs Fm./St. Claire Ls.
Silurian			Sexton Creek Ls.	Bainbridge Gr. Sexton Creek Ls.	Sexton Creek Ls.
	AQT2 (L4)	Shale	Maquoketa Gr.	Maquoketa Gr.	Maquoketa Gr.
Ordovician	AQF2 (L3)	Carbonates and sandstone	Galena Gr./Platteville Gr./St. Peter Ss.	Black River Gr./Ancell Gr.	Black River Gr./St. Peter Ss.
		Carbonates	Knox Gr.	Knox Gr.	Knox Gr.
Cambrian	AQT1 (L2)	Predominantly shale	Eau Claire Fm.	Eau Claire Fm.	Eau Claire Fm.
	AQF1 (L1)	Predominantly sandstone	Mount Simon Ss.	Mount Simon Ss.	Mount Simon Ss.





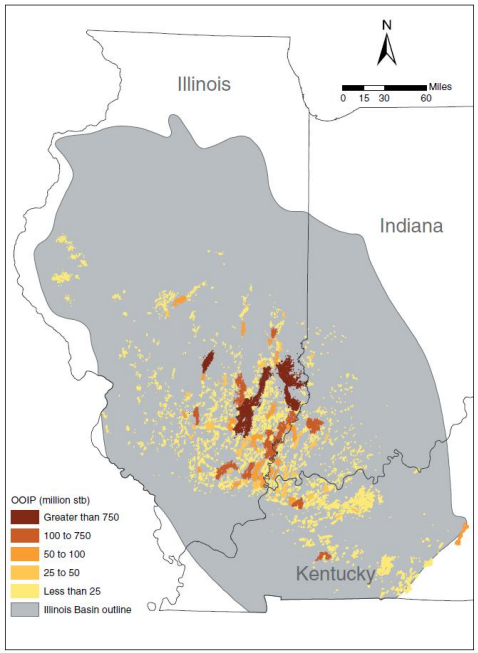


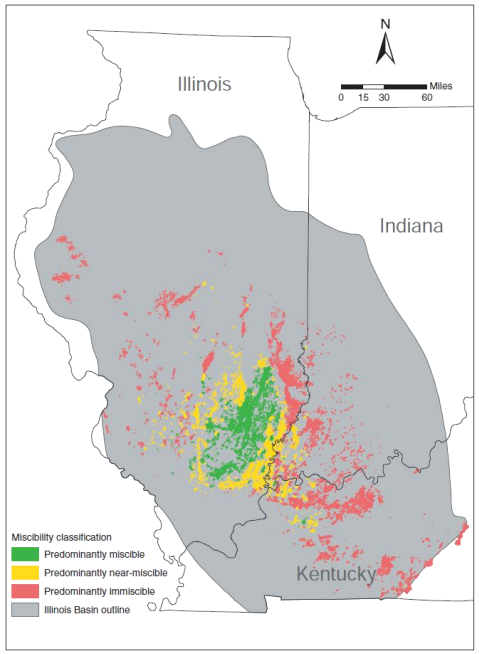


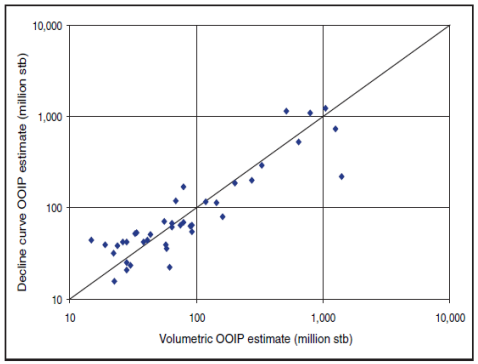
Storage: Oil and gas reservoirs (EOR)

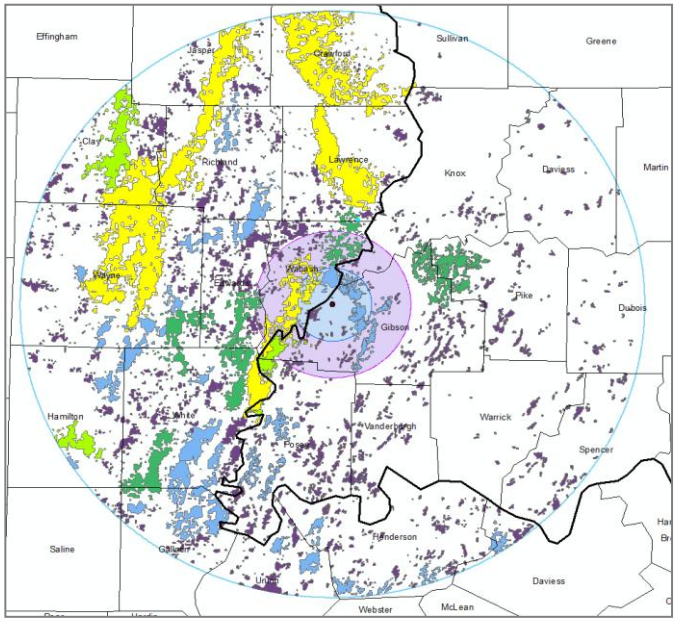
Oil and Gas Reservoirs

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





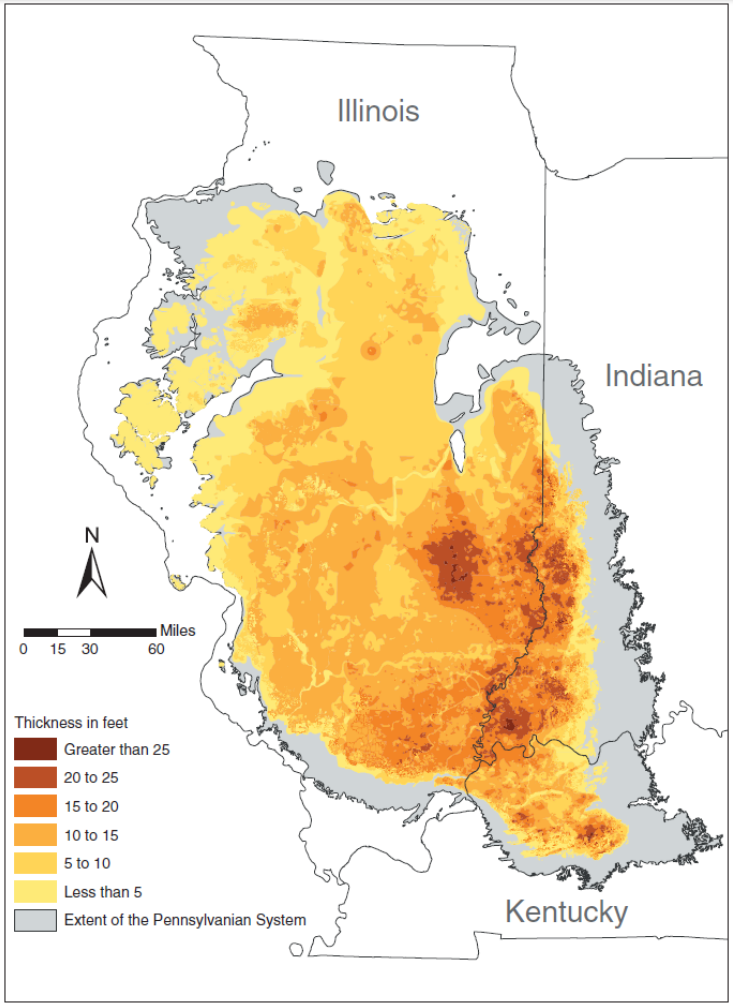




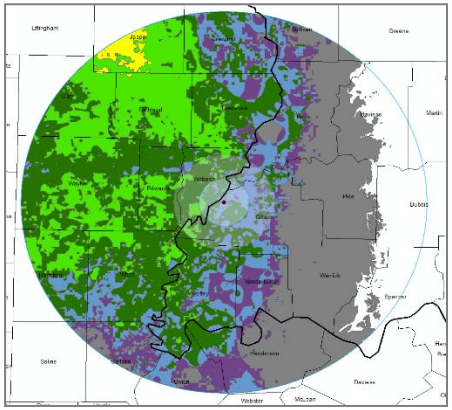
Storage: Enhanced Coalbed Methane (ECBM)

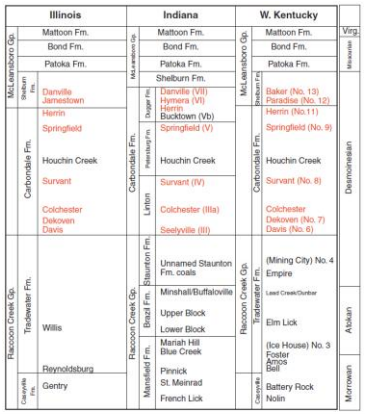
Coal seams

- Extensive mapping of all Pennsylvanian seams
- COMET model simulations of CO_2 injection and methane production for 80-acre 5-spot pattern with parameter distributions at 3 depth divisions
- Gas recovery and storage efficiency factors from COMET modeling applied in ArcGIS for volumetric calculations of ECBM and CO_2 storage estimates



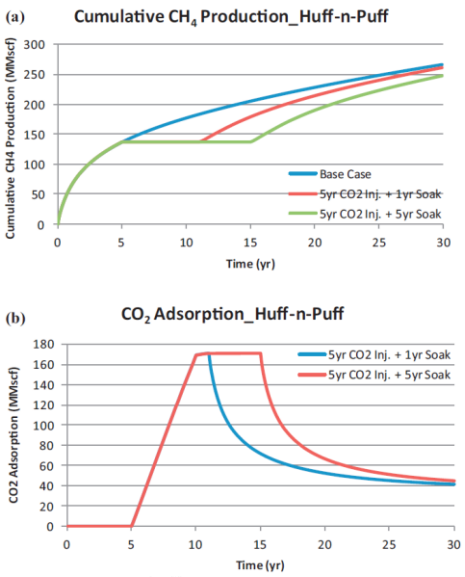
Illinois Basin seam	ECBM recoverable (billion scf)	CO_2 storage (billion scf)	CO_2 storage (million tonnes)
Danville/Baker	807	8,299	440
Hymera/Jamestown/Paradise	200	2,073	110
Herrin	903	9,758	518
Springfield	1,252	13,511	717
Survant	1,081	10,978	582
Colchester	1,274	12,583	668
Seelyville/Davis/Dekoven	1,163	11,349	602
Illinois Basin total	6,680	68,550	3,637

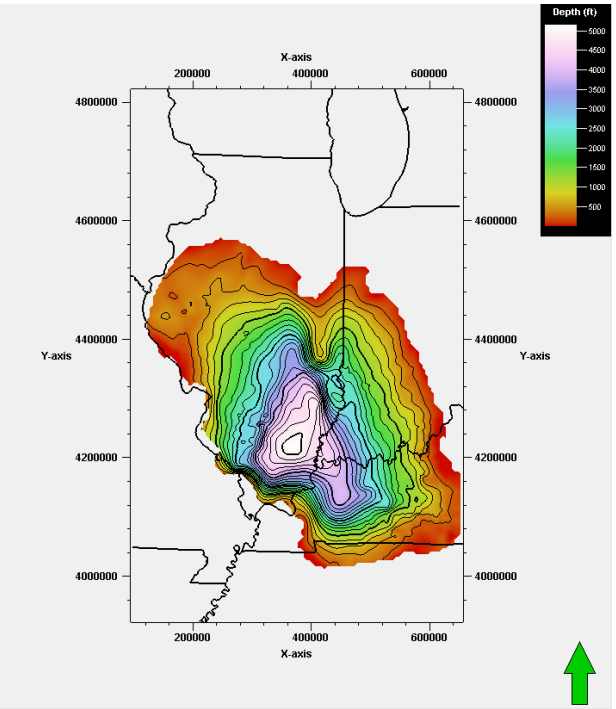


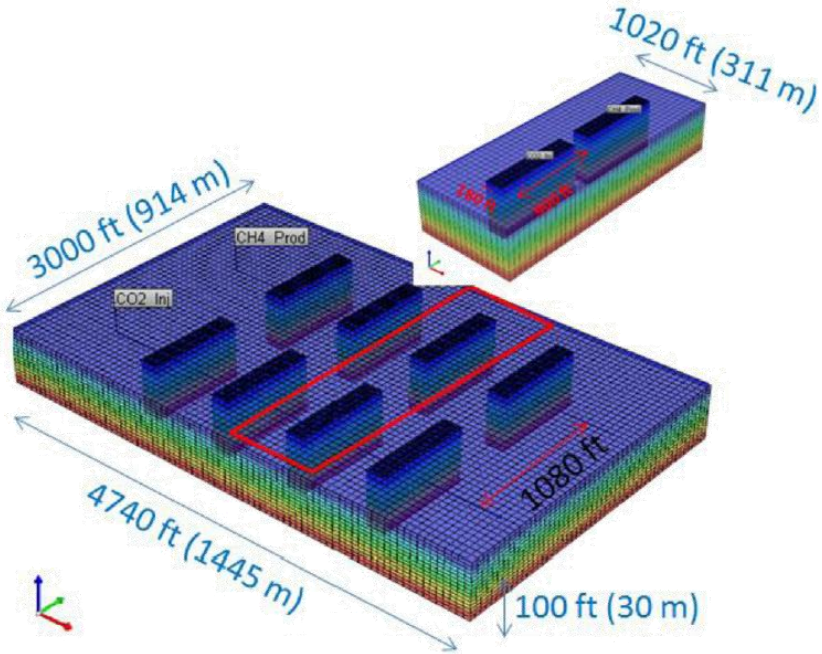


Storage: New Albany Shale

- Organic-rich New Albany Shale formation
- Extensive mapping throughout the basin
- Density logs from 131 wells used to estimate TOC OGIP f(P, TOC) calculated from normal pressure assumption (hydrostatic) and Langmuir adsorption isotherms from measured data (high and low TOC samples) interpolated to estimate NAS average (TOC = 5.49%).



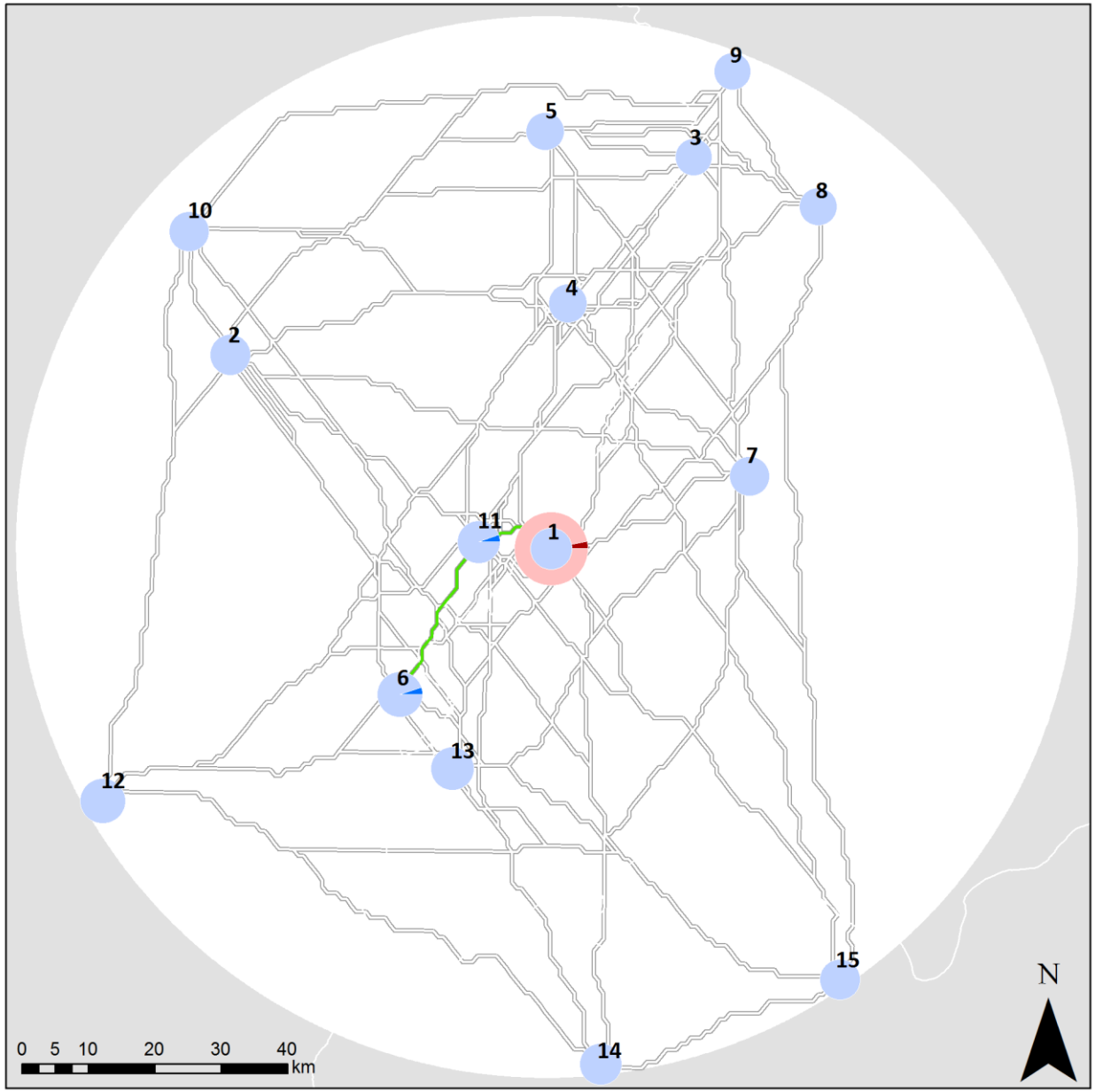




Scenario 1: CO_2 cap (0.5 to 15 $MtCO_2$/yr)

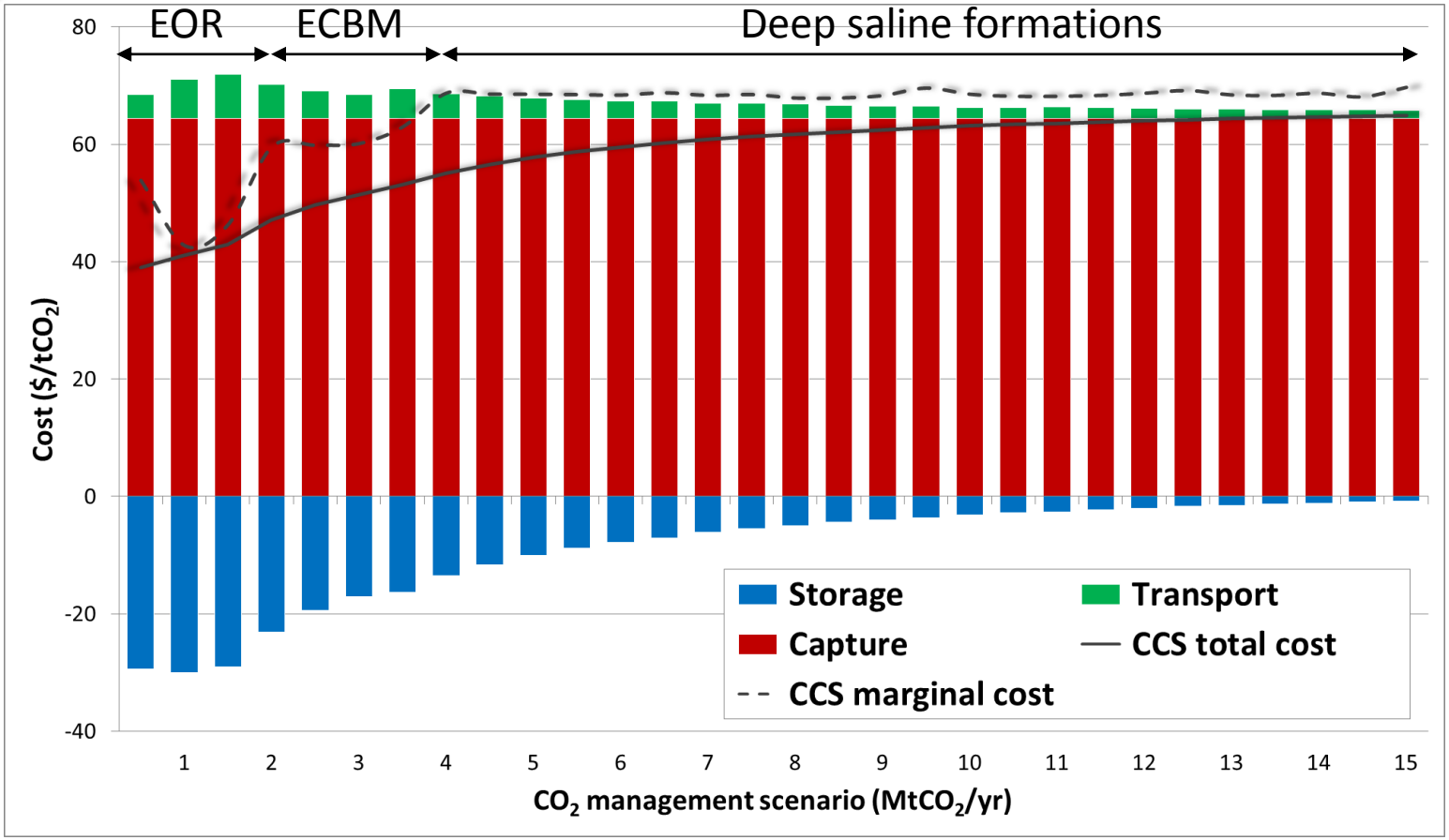
Click images to activate animation

- 0.5 $MtCO_2$/yr
- 1 $MtCO_2$/yr
- 1.5 $MtCO_2$/yr
- 2 $MtCO_2$/yr
- 2.5 $MtCO_2$/yr
- 3 $MtCO_2$/yr
- 3.5 $MtCO_2$/yr
- 4$MtCO_2$/yr
- 4.5 $MtCO_2$/yr
- 5 $MtCO_2$/yr
- 5.5 $MtCO_2$/yr
- 6 $MtCO_2$/yr
- 6.5 $MtCO_2$/yr
- 7 $MtCO_2$/yr
- 7.5 $MtCO_2$/yr
- 8 $MtCO_2$/yr
- 8.5 $MtCO_2$/yr
- 9 $MtCO_2$/yr
- 9.5 $MtCO_2$/yr
- 10 $MtCO_2$/yr
- 10.5 $MtCO_2$/yr
- 11 $MtCO_2$/yr
- 11.5$MtCO_2$/yr
- 12 $MtCO_2$/yr
- 12.5 $MtCO_2$/yr
- 13 $MtCO_2$/yr
- 13.5$MtCO_2$/yr
- 14 $MtCO_2$/yr
- 14.5 $MtCO_2$/yr
- 15 $MtCO_2$/yr



Analysis: storage infrastructure costs

MENU
SimCCS
Case study
Storage
Results
Geospatial
Costs
Pipelines
CO_2 tax
Dynamics
Future work
Conclusions



- Reservoirs deploy according to CO_2 "credit"
- EOR/ECBM offset storage costs, even at 15 $MtCO_2$/yr
- Economies of scale drives down transport costs
- Marginal costs drive CCUS decisions

Analysis: pipeline network

MENU
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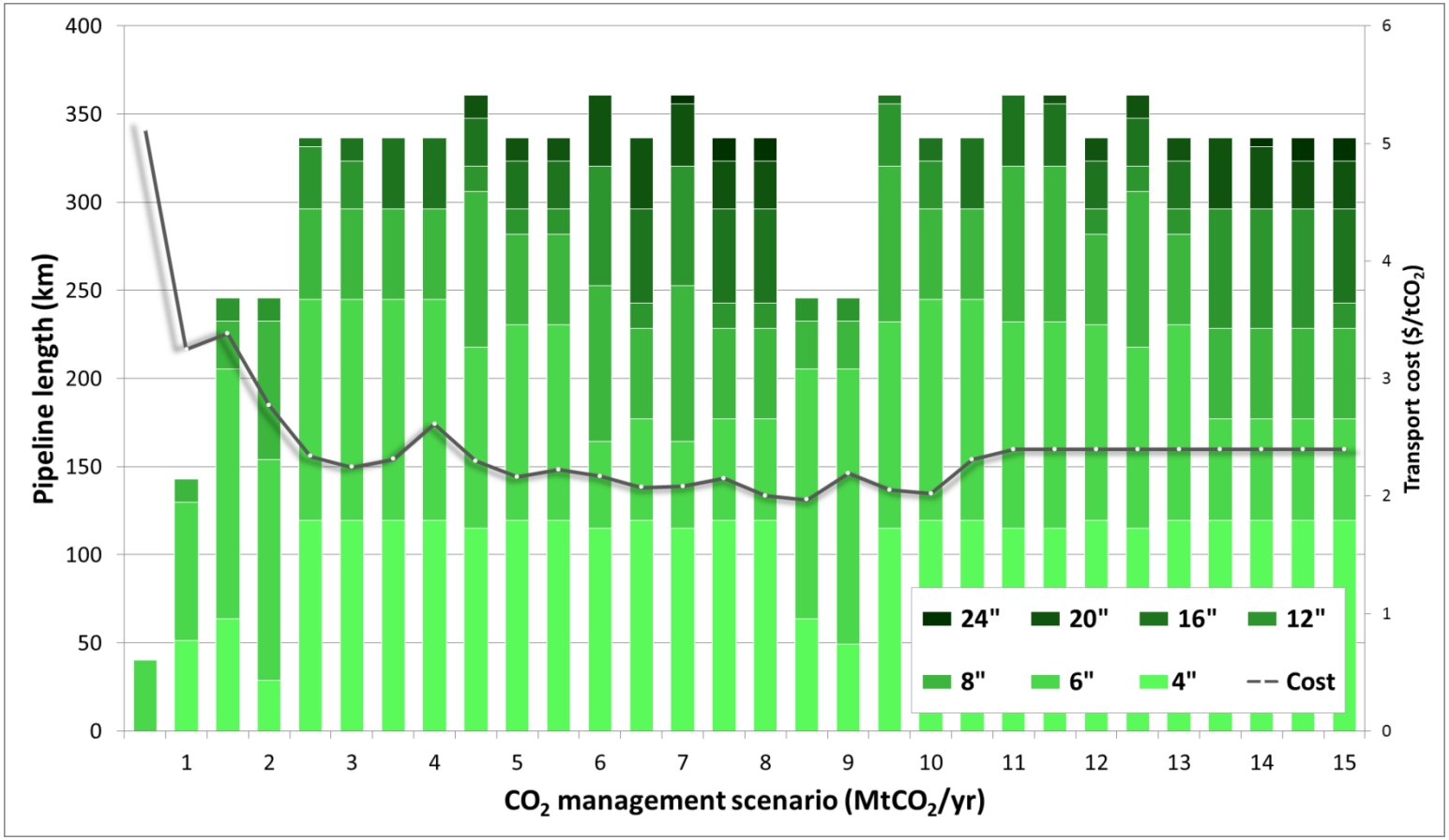

- Reservoirs deploy according to CO_2 "credit"
- EOR/ECBM offset storage costs, even at 15 $MtCO_2$/yr
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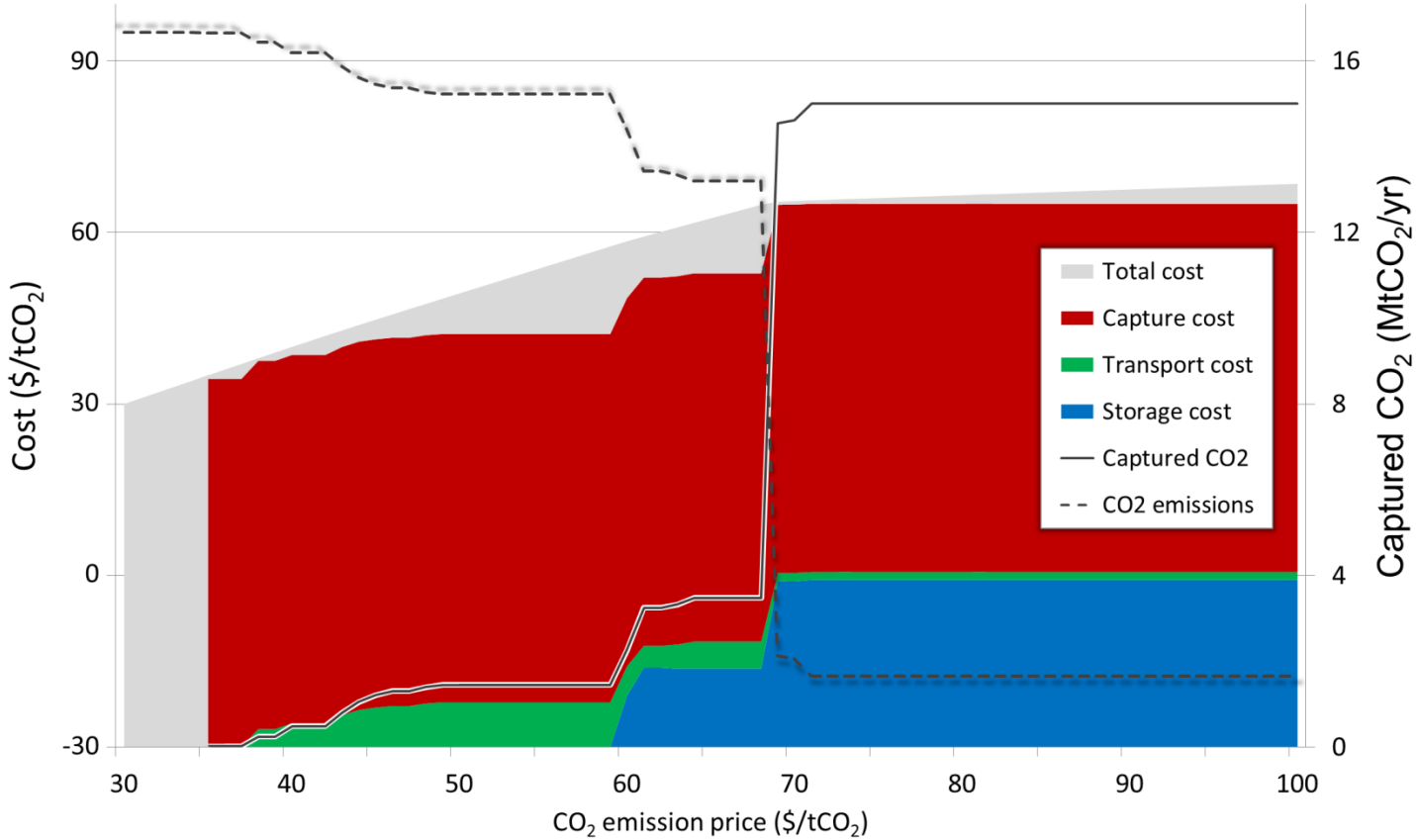
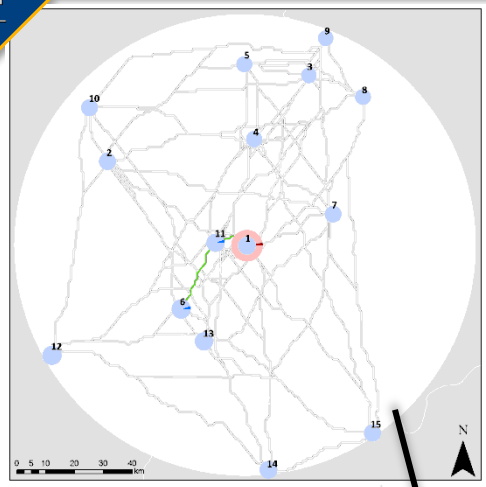
- Marginal costs drive CCUS decisions

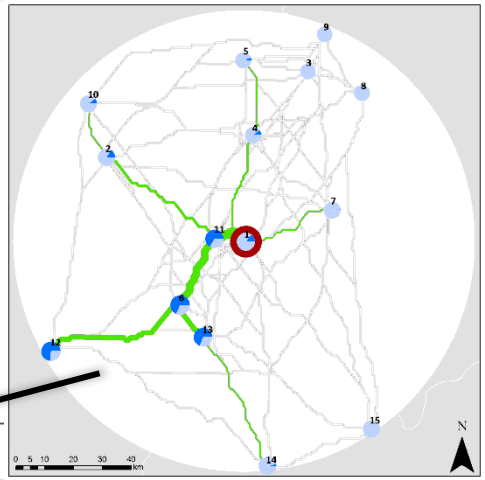
Scenario 2 Analysis: CO_2 tax

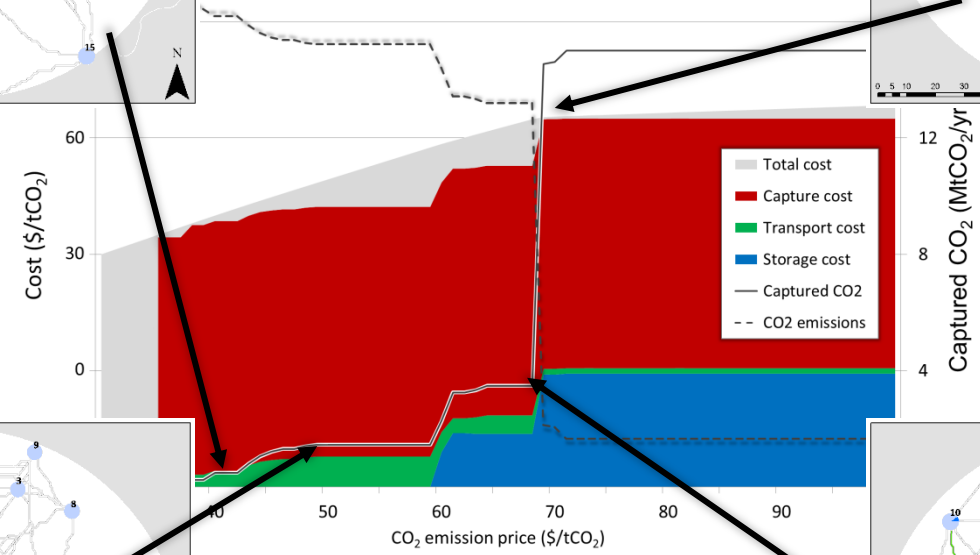


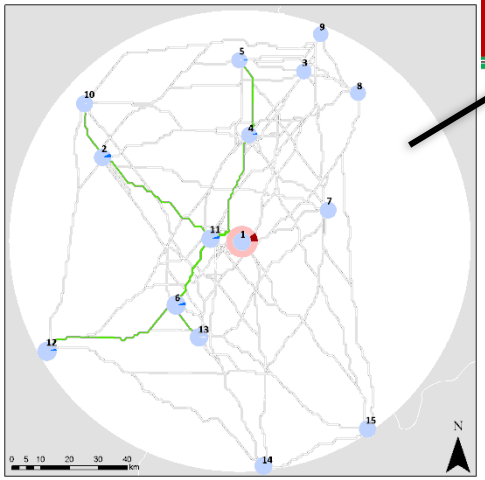
- Estimate infrastructure in response to CO_2 tax
- 10% emissions cannot be captured and is subject to CO_2 tax
- CO_2 stored using EOR until ~$60/tCO

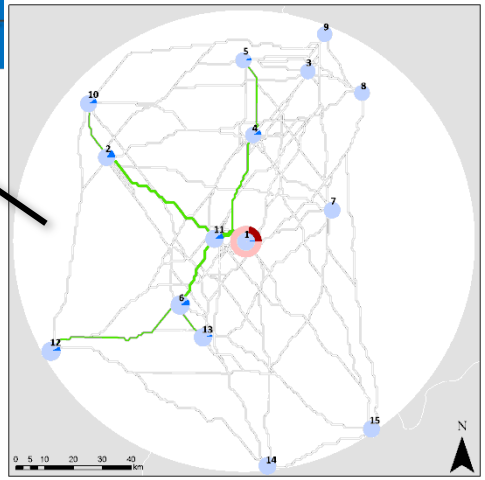
Scenario 2 Analysis: CO_2 tax





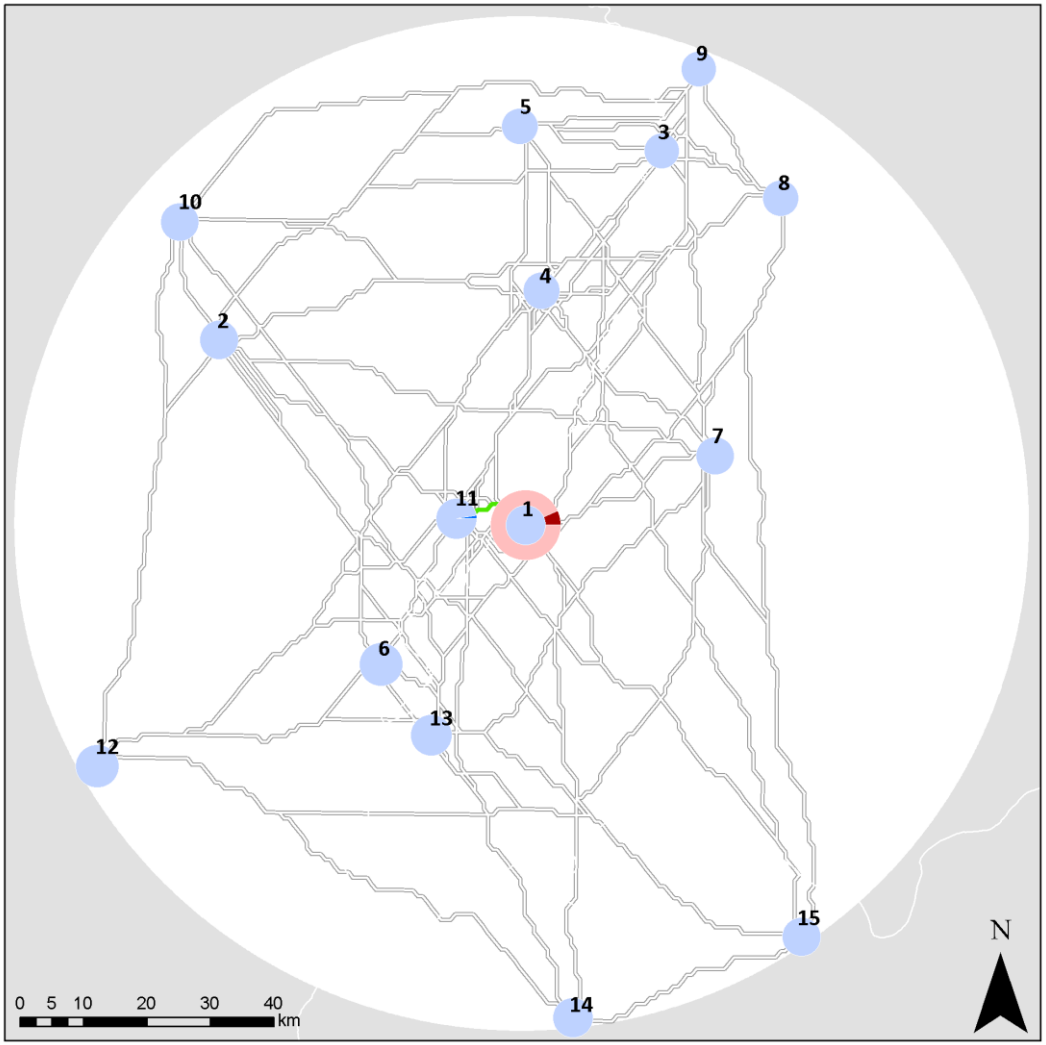






Scenario 3 Analysis: Dynamic CCUS Infrastructure

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



Click images to activate animation

Project period	CO_2 target	Cumulative CO_2
1-3 yrs	1 $MtCO_2$/yr	3 $MtCO_2$
4-6 yrs	2 $MtCO_2$/yr	9 $MtCO_2$
7-9 yrs	3 $MtCO_2$/yr	18 $MtCO_2$
10-12 yrs	4 $MtCO_2$/yr	30 $MtCO_2$
13-15 yrs	5 $MtCO_2$/yr	60 $MtCO_2$
16-30 yrs	10 $MtCO_2$/yr	117 $MtCO_2$

Conclusion

Making CCUS a reality will require rigorous integration of extensive R&D results into a business plan framework

- Robust analysis needs for capture and storage (costs, capacities, injection rates), emission costs & prices, policies, energy prices…
- New certainty in the USA on power plant emissions.
- Identify hidden opportunities for CCUS implementation via CO_2 utilization.

Significant innovations with SimCCUS

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