

Economics, Modeling and CO₂ Management:

Developing Policy Insight with Data Uncertainty

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and

Jason E. Heath, Thomas Dewers, Jesse D. Roach, Geoffrey T. Klise,
and many others.

Society for Industrial and Applied Mathematics (SIAM)

Conference on Mathematical & Computational Issues in the Geosciences

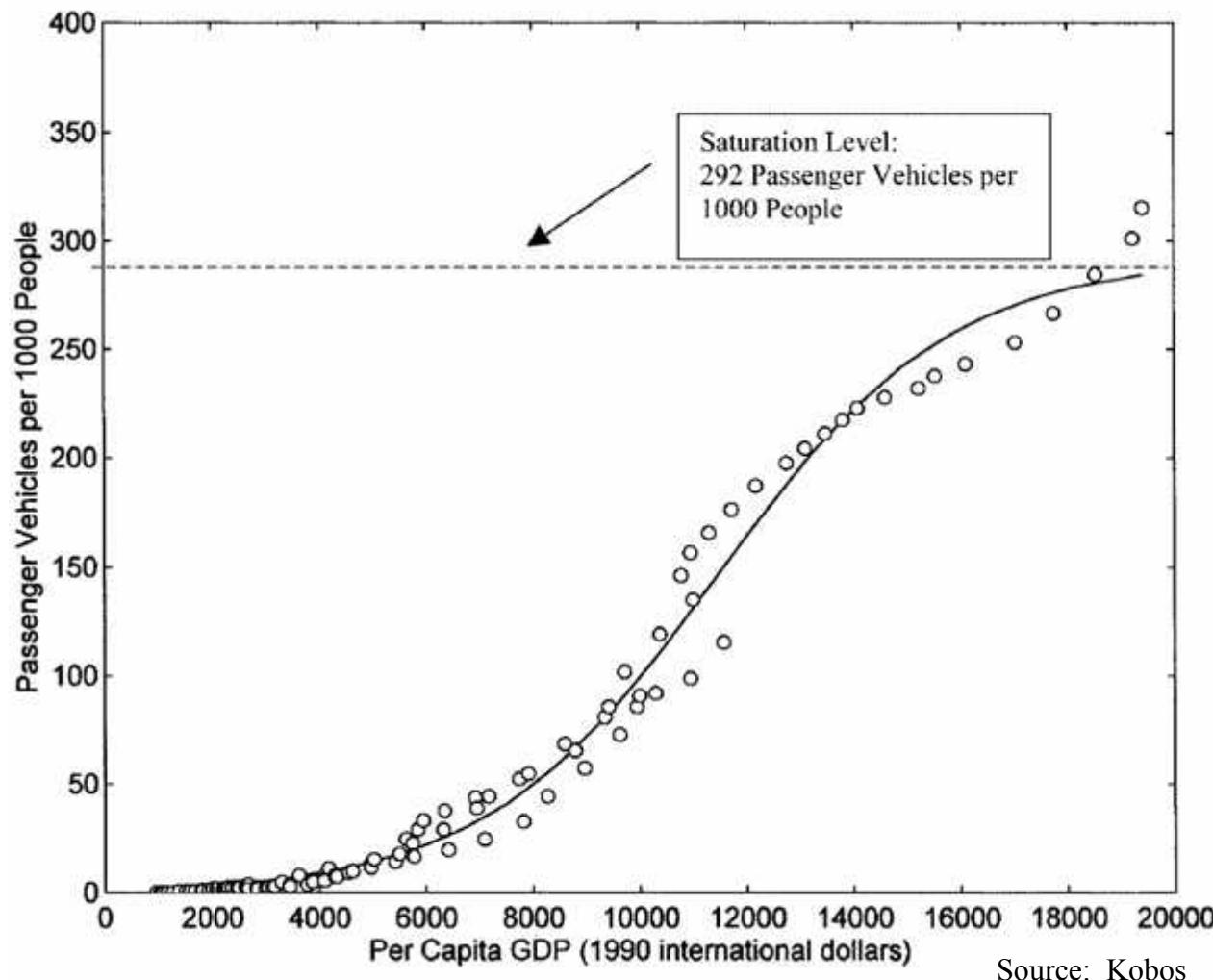


Mathematical Modeling Approaches for Energy Policy Planning

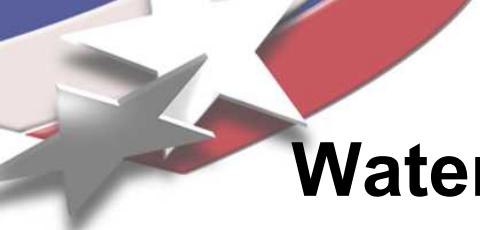
- **Top-down**
 - Energy sector, economy-wide, Computable General Equilibrium (CGE)
 - Useful for simulating taxes and externalities for economic costs
 - e.g., Input-Output Analysis, Jorgenson-Wilcoxen Model (CGE)
- **Bottom-up**
 - Simulation / optimization, technology descriptive
 - Useful for selecting fuel and technology choices
 - e.g., Least-Cost optimization models, MARKAL, MESSAGE, NEMS
- **Hybrid / Integrated Assessment Models**
 - Builds on the strengths of both Top-down and Bottom-up methods
 - Economic tools, technology, builds the systems view from several sets of detailed components
 - Useful to develop technology rich analysis modules combined with economic/policy insight

Bottom-Up Product Adoption Forecasting: *Employing the Bootstrap Method*

Estimating Market Saturation of Passenger Vehicle Ownership



Source: Kobos



Building a Framework for Water, Energy and CO₂ Storage (WECS): *Addressing Uncertainty in the Data*

(4) H₂O Treatment & Use



(1) CO₂ Capture

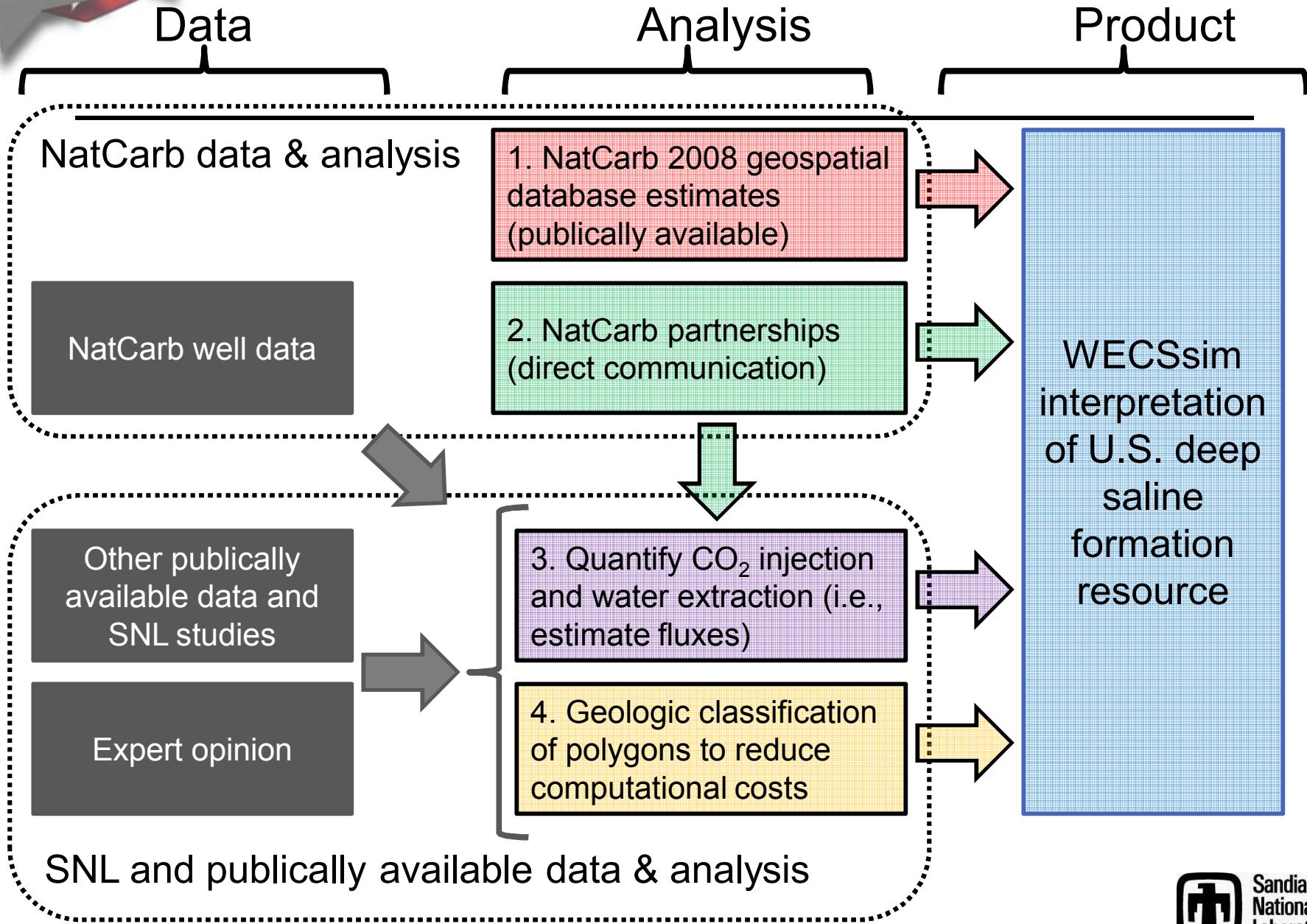


**(3) H₂O
Extraction**

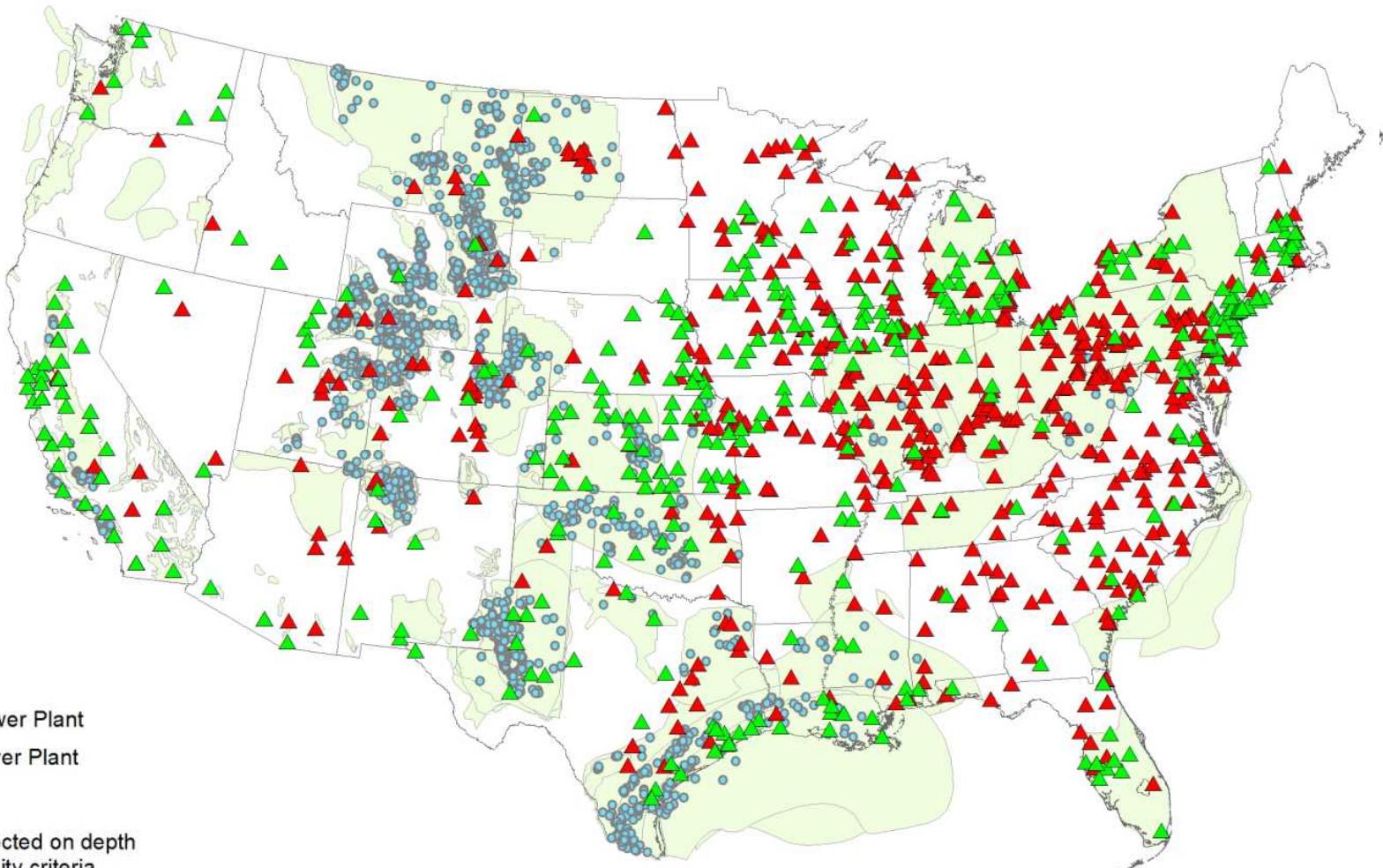
**(2) Formation
Assessment
& CO₂ Storage**

Geologic Saline Formation

Assessing U.S. deep saline formations



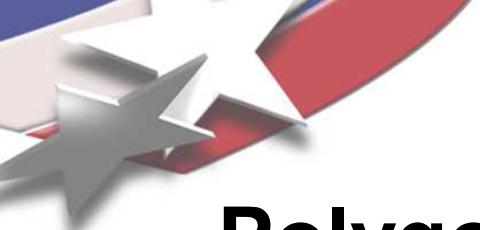
Geological CO₂ Storage Database is Incomplete: *Makes Source/Sink Matching Difficult*



Legend

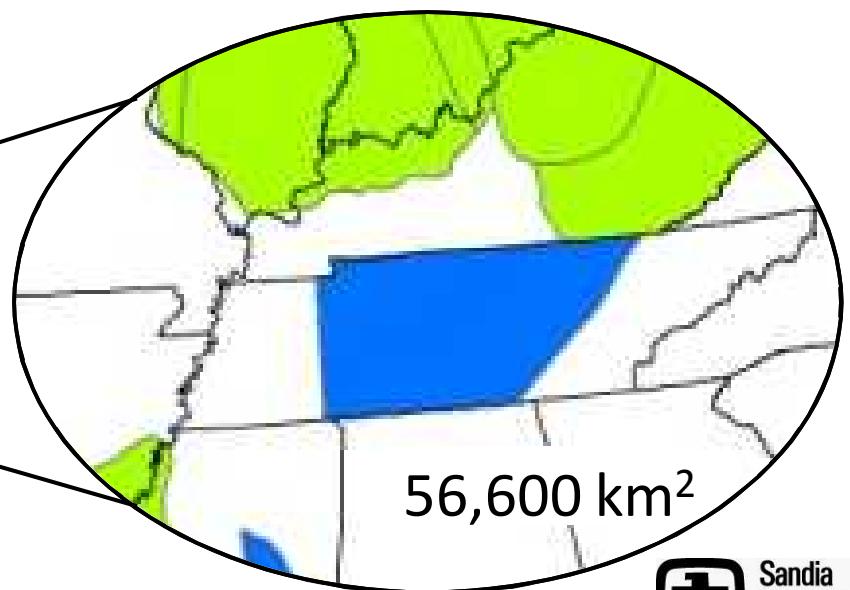
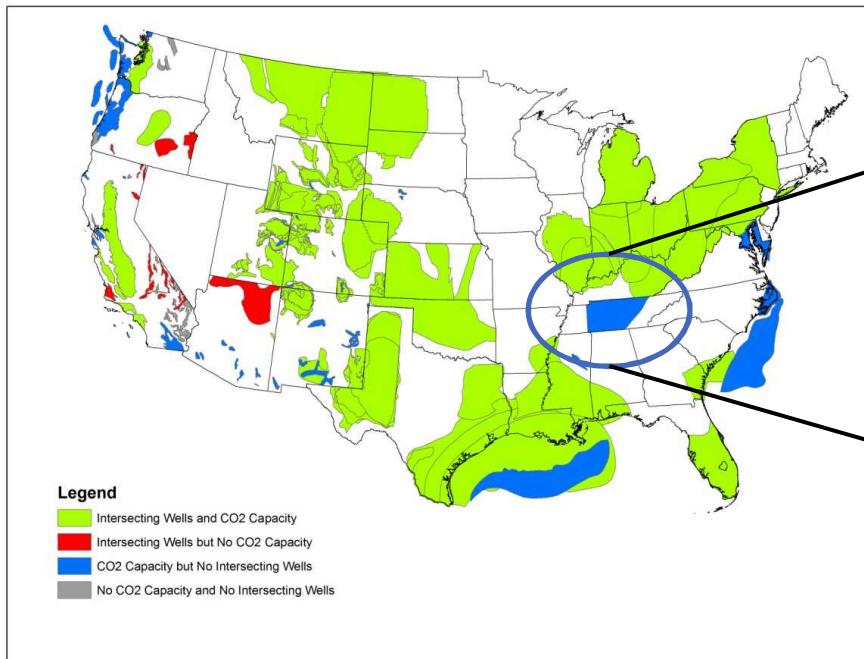
- ▲ Coal Power Plant
- ▲ Gas Power Plant
- Well
- Well selected on depth and salinity criteria

325 downselected formations from
original NatCarb Atlas data



Mt. Simon Sandstone: Polygon in Tennessee w/sparse data

- One of the 47 polygons lacking desired information in NatCarb:
 - Depth, thickness, porosity, permeability, pressure, temperature, and salinity information
 - Any potentially intersecting wells (in the well databases we evaluated).





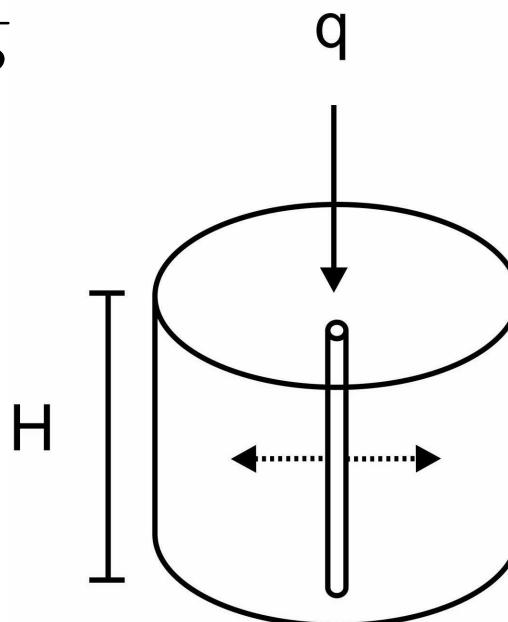
Uncertainty and the Well Injectivity Index

I well injectivity index;
measure of the “ease”
of injecting CO₂ into
the well

q volumetric flow rate

ΔP the pressure gradient

$$I \equiv \frac{q}{\Delta P}$$



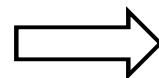
Reservoir Volume

$$I = \frac{4\pi k k_r H}{\mu \left(\ln \left(\frac{4A}{1.781 C_A r_w^2} \right) + 2s \right)}$$

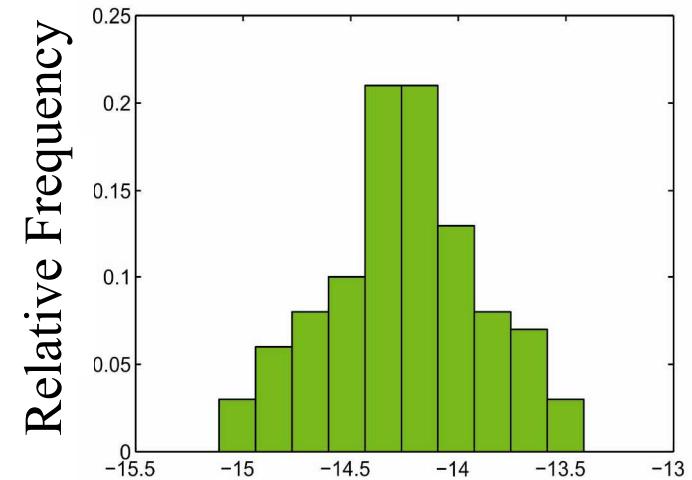
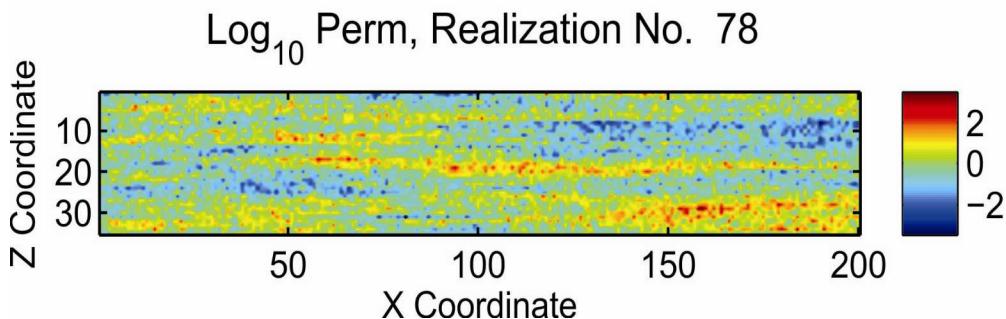
Radial flow from the
well

Generating pdfs of Well Injectivity Index

Use geostatistics to generate multiple realizations of relevant parameter fields



Average key parameters of each realization, giving pdfs for the parameters



Log₁₀(averaged permeability)

Feed the averaged parameters into equation to get a pdf of I

$$I = \frac{4\pi k k_r H}{\mu \left(\ln \left(\frac{4A}{1.781 C_A r_w^2} \right) + 2s \right)}$$

Power plant generated carbon sequestration in saline formations

a dynamic analysis tool

Summary

Selected Sequestration Formation

Partnership	Basin Name	Formation Name
SECARB	Gulf Coast	Eocene Sand

Locations of Formation & Power Plant

Formation Centroid Location

Latitude	Longitude
31°41'3.48"	-89°53'54.96"

Power plant to formation distance

Default	8 mi
Custom	0 mi

Formation Shape and Areal Extent

Default	149 mi	193 mi
Custom	134 mi	147 mi
Total	283 mi	340 mi

Formation Footprint Area

Default	63.33 mi ²
Custom	60.71 mi ²
Total	120.04 mi ²

Sequestration Depth at Sequestration Depth

Default	8400 ft
Custom	8300 ft
Range	8200 ft - 8500 ft

Temperature at Sequestration Depth

Default	88°C
Custom	87°C
Range	86°C - 89°C

Pressure at Sequestration Depth

Default	105 atm
Custom	102 atm
Range	100 atm - 108 atm

Formation Thickness

Default	800 ft
Custom	800 ft
Range	780 ft - 820 ft

Formation Porosity

Default	0.15
Custom	0.15
Range	0.13 - 0.17

Formation Permeability

Default	82 mD
Custom	82 mD
Range	80 mD - 84 mD

Number of injection wells

Default	10
Custom	8
Range	8 - 12

Steady State Density Sequestered CO₂

Default	200 kg/m ³
Custom	200 kg/m ³
Range	190 kg/m ³ - 210 kg/m ³

Sequestration Efficiency

Default	95%
Custom	95%
Range	90% - 100%

CO₂ Storage Capacity

Default	778,320 Mm ³
Custom	781,377 Mm ³
Range	773,443 Mm ³ - 784,882 Mm ³

Distance from source to sink (as the crow flies): 8.0 mi

Steady state temperature at sequestration depth: 83.6°C

Steady state pressure at sequestration depth: 103.2 atm

Steady state density of CO₂ in sequestration formation: 204 kg/m³

Selected life of sequestration formation for selected source: 67,000 yr

Number of sequestration (injection) wells needed: 10

Total rate of sequestration: 0.03 Mm³/yr

Levelized cost of CO₂ transport and sequestration: 0.05 cents/kWh

Power Plant

Carbon Capture

Carbon Sequestration

Extracted Water

Power Costs

Input

Selected Sequestration Formation

Partnership	Basin Name	Formation Name
<input checked="" type="radio"/> Model Default:	SECARB	Gulf Coast
<input type="radio"/> Custom: (changeable with dropdown)	SE_TG_TUS	
	SECARB	Tuscaloosa Group
		Tuscaloosa Group

Locations of Formation & Power Plant

Formation Centroid Location

Latitude	Longitude
36°	-108°

Power plant to formation distance

Default	189 mi
Custom (changeable)	0 mi

Formation Shape and Areal Extent

Approximate formation extent from centroid in 8 directions

Default	NW	N	NE
	139 mi	199 mi	87 mi
	81 mi	Centroid	107 mi
	78 mi	201 mi	143 mi
Custom	SW	S	SE
	14 mi	13 mi	12 mi

Maximum distance power plant to default formation

Representing potential institutional constraints on moving extracted water back to power plant

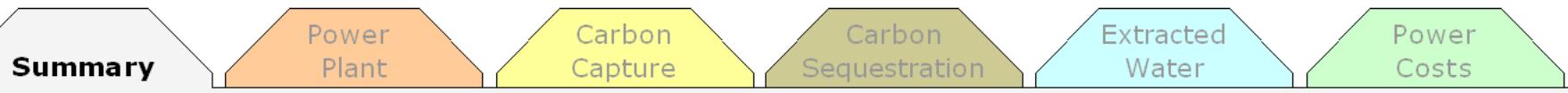
Formation Footprint Area

Calculated based on geometry specified to the left, or input directly here

 Sandia
National
Laboratories

Power plant generated carbon sequestration in saline formations

a dynamic analysis tool



General Summary

Power Plant Specifications	1,848 MW	PC Subcritical
% CO2 Captured	90 %	
LCOE Increase	51 %	
Cost of Avoided CO2 Emissions	\$65 per tonne	
H2O Demand Increase	12.5 MGD	58 %
Distance to Sequestration Formation	6 mi	
Formation Life For This CO2 Only	73,000 yr	
% H2O Demand Increase Served	60 %	

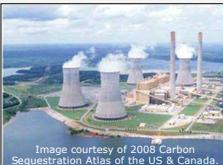


Image courtesy of 2008 Carbon Sequestration Atlas of the US & Canada.

Power Plant Summary

(Power Plant tab for details or to change values.)

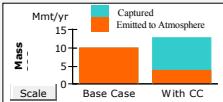
Power Plant Type	Pulverized coal subcritical
Latitude and Longitude	30° -94°
Base Electricity Production	11.5 TWh/yr
Base CO2 Production	9.9 Mmt/yr
Base H2O Withdrawals	21.4 MGD
Base H2O Consumption	6 billion gal/yr



Carbon Capture (CC) Summary

(Carbon Capture tab for details or to change values.)

% Base CO2 Captured	90 %
Parasitic Energy Loss	30 %
Make-Up-Power (MUP) CO2 Production	2.8 Mmt/yr
% MUP CO2 Captured	0 %
MUP and CC H2O Withdrawals	12.5 MGD



Carbon Sequestration (CS) Summary

(Carbon Sequestration tab for details or to change.)

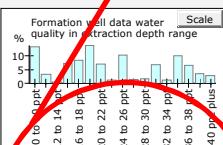
CO2 To Be Sequestered	8.9 Mmt/yr
Target Sink Centroid Lat-Long	29°59'35" -93°53'58"
Power Plant to Sink (centroid) Distance	6 mi
Target Sink Partnership	SECARB
Target Sink Basin Name	Gulf Coast
Target Sink Formation Name	Eocene Sand
Sink Life for this CO2 only	73,000 yr



Extracted Water Summary

(Extracted Water tab for details or to change values.)

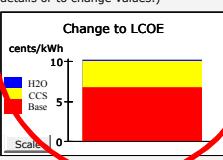
Rate of Water Extraction	10.1 MGD
Treated Water Stream	7.6 MGD
% CCS Related Water Demand Served	60 %
Extracted Water Target Quality	10 ppt to 30 ppt
Number of Extraction Wells	21
Extraction Well Depth Range	2500' to 5000'
Brine Disposal Method	Reinjection



Power Costs Summary (2010 \$)

(Power Costs tab for details or to change values.)

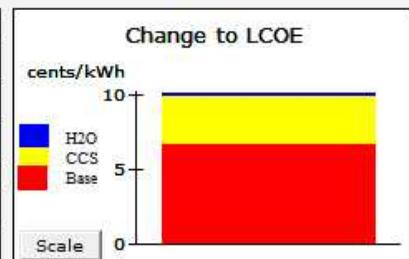
Base Electricity Levelized Cost of Energy (LCOE)	6.7 cents/kWh
CO2 Capture & Compression Additions to LCOE	3.2 cents/kWh
CO2 Transport & Sequestration Additions to LCOE	0 cents/kWh
H2O Extraction & Treatment Additions to LCOE	0.2 cents/kWh
Total New LCOE	10.1 cents/kWh
LCOE % Increase Due to CCS	51 %
Cost of Avoided CO2 Emissions to Atmosphere	\$65 per tonne



Power Costs Summary (2010 \$)

(Power Costs tab for details or to change values.)

Base Electricity Levelized Cost of Energy (LCOE)	6.7 cents/kWh
CO2 Capture & Compression Additions to LCOE	3.2 cents/kWh
CO2 Transport & Sequestration Additions to LCOE	0 cents/kWh
H2O Extraction & Treatment Additions to LCOE	0.2 cents/kWh
Total New LCOE	10.1 cents/kWh
LCOE % Increase Due to CCS	51 %
Cost of Avoided CO2 Emissions to Atmosphere	\$64 per tonne



Power plant generated carbon sequestration in saline formations

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Summary

Power Plant

Carbon Capture

Carbon Sequestration

Extracted Water

Power Costs

Power Plant Specs:

Power Plant Type

- Pulverized coal subcritical
- Pulverized coal supercritical
- Integrated gasification combined cycle
- Natural gas turbine
- Natural gas combined cycle

Power Plant Location



Latitude: 30° Longitude: -90°

(click # to change)

Installed Capacity

0 1,000 2,000 3,000 4,000 MW

1,845 MW

Capacity Factor

0 0.2 0.4 0.6 0.8 1.0

0.72

CO2 Production Rate

<input type="radio"/> Use default:	1,900 lbs/MWh
<input type="radio"/> Use custom: (click # to change)	1,200 lbs/MWh

Defaults based on Exhibit 9-2 in NETL-2007/1281

Expected Year Online and Offline

Start Yr	End Yr
<input type="radio"/> Existing plant:	NA
<input type="radio"/> New plant build: (click # to change)	2010 2040

Cooling Technology

- Once through
- Cooling tower(s)
- Cooling pond(s)
- Dry cooling

Base Water Use Rates

Withdrawal	Consumption
<input checked="" type="radio"/> Use default	670 gal/MWh 520 gal/MWh
<input type="radio"/> Use custom: (click # to change)	670 gal/MWh 520 gal/MWh

Defaults based on Tables D-1 and D-4 of NETL 400/2008/1339 and Figure 4-2 and B-1 of NETL 402/08018

Base Levelized Cost of Electricity (LCOE)

Total	Fuel Costs	Cooling	All Other	\$ Year:
<input checked="" type="radio"/> Default:	6.7 cents/kWh	= 2.1 cents/kWh + 0.3 cents/kWh	+ 4.4 cents/kWh	2010
<input type="radio"/> Custom: (changeable)	6.4 cents/kWh	= 2 cents/kWh + 0.2 cents/kWh	+ 4.2 cents/kWh	2007

Defaults based on Exhibits 3-2, 3-29, 3-62, 3-95, 4-12, 4-33, 5-12 in NETL 2007/1281 and Figure 13 of Tawney, Khan, Zachary, Journal of Engineering for Gas Turbines and Power, April 2005, V 127

Output

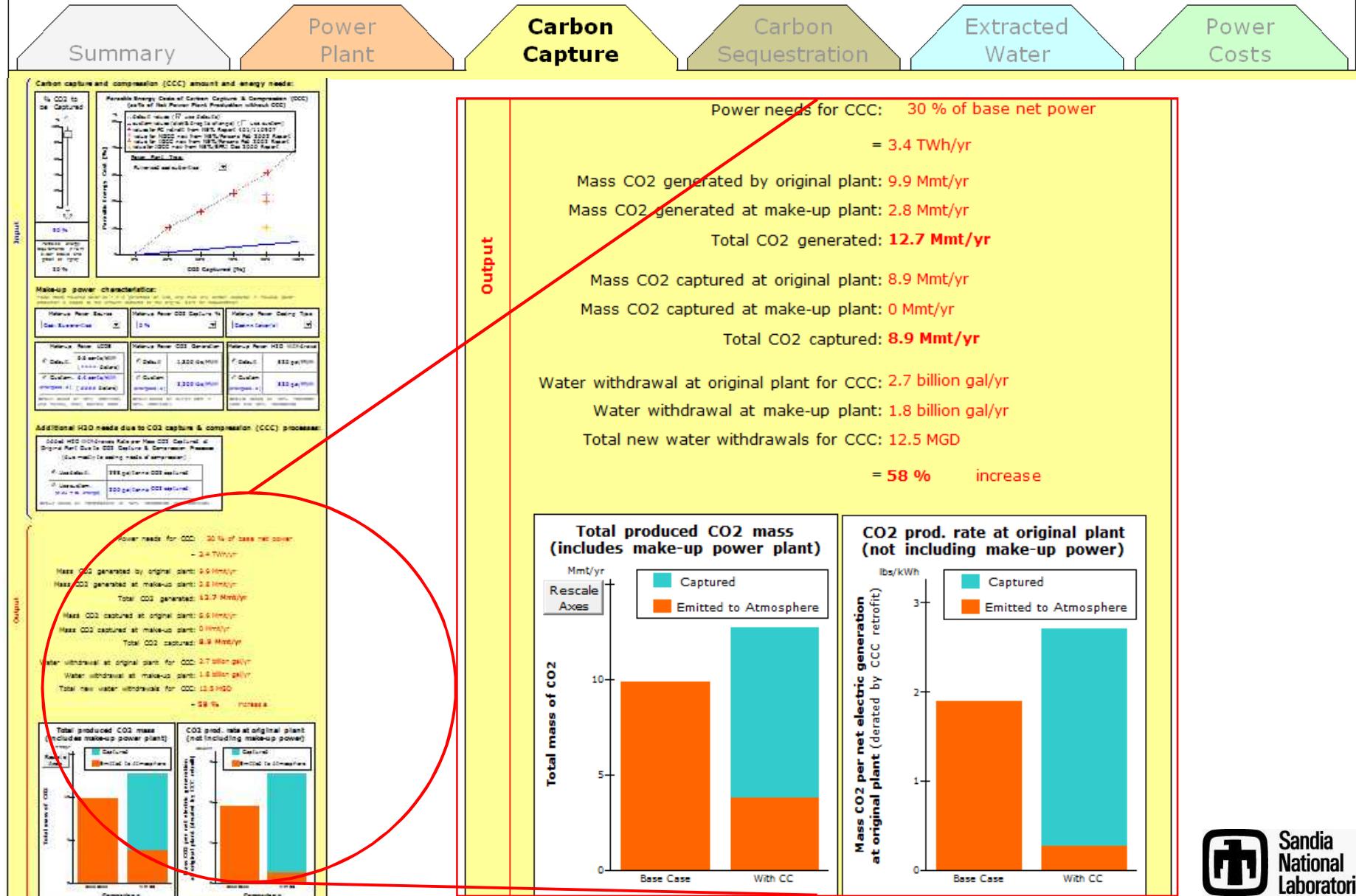
Annual electricity generation: 11.5 TWh/yr
 Annual CO2 generation: 9.9 Mmt/yr
 Annual H2O withdrawals: 21.4 MGD
 Annual H2O consumption: 6 billion gal/yr

This plant would generate more electricity than **97 %** of all fired plants in the U.S. in 2005.
 This plant would generate more CO2 than **96 %** of all fired plants in the U.S. in 2005.
 This plant has a capacity greater than **96 %** of all fired plants in the U.S. in 2005.
 This plant has a capacity factor greater than **75 %** of all fired plants in the U.S. in 2005.
 This plant has a CO2 emission rate greater than **26 %** of all fired plants in the U.S. in 2005.

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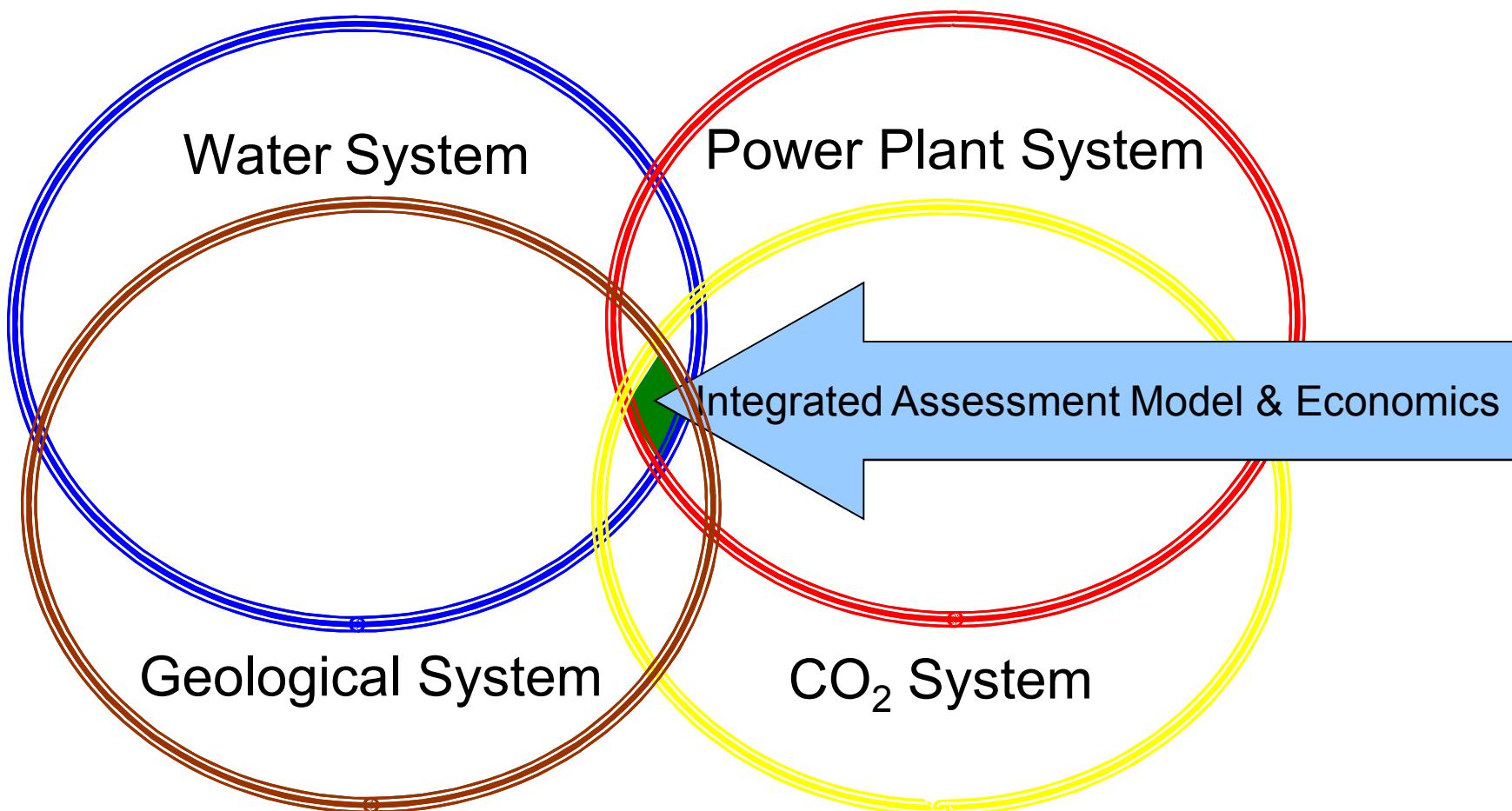
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Improving Confidence in the Integrated Assessment Model by Addressing Uncertainty





Economics, Modeling and CO₂ Management:

Developing Policy Insight with Data Uncertainty

Thank you.

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Conference on Mathematical & Computational Issues in the Geosciences