



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

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National Nuclear Security Administration under contract DE-AC04-94AL85000. Working Results.



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-Wilcoxon Model (CGE)

- **Bottom-up**

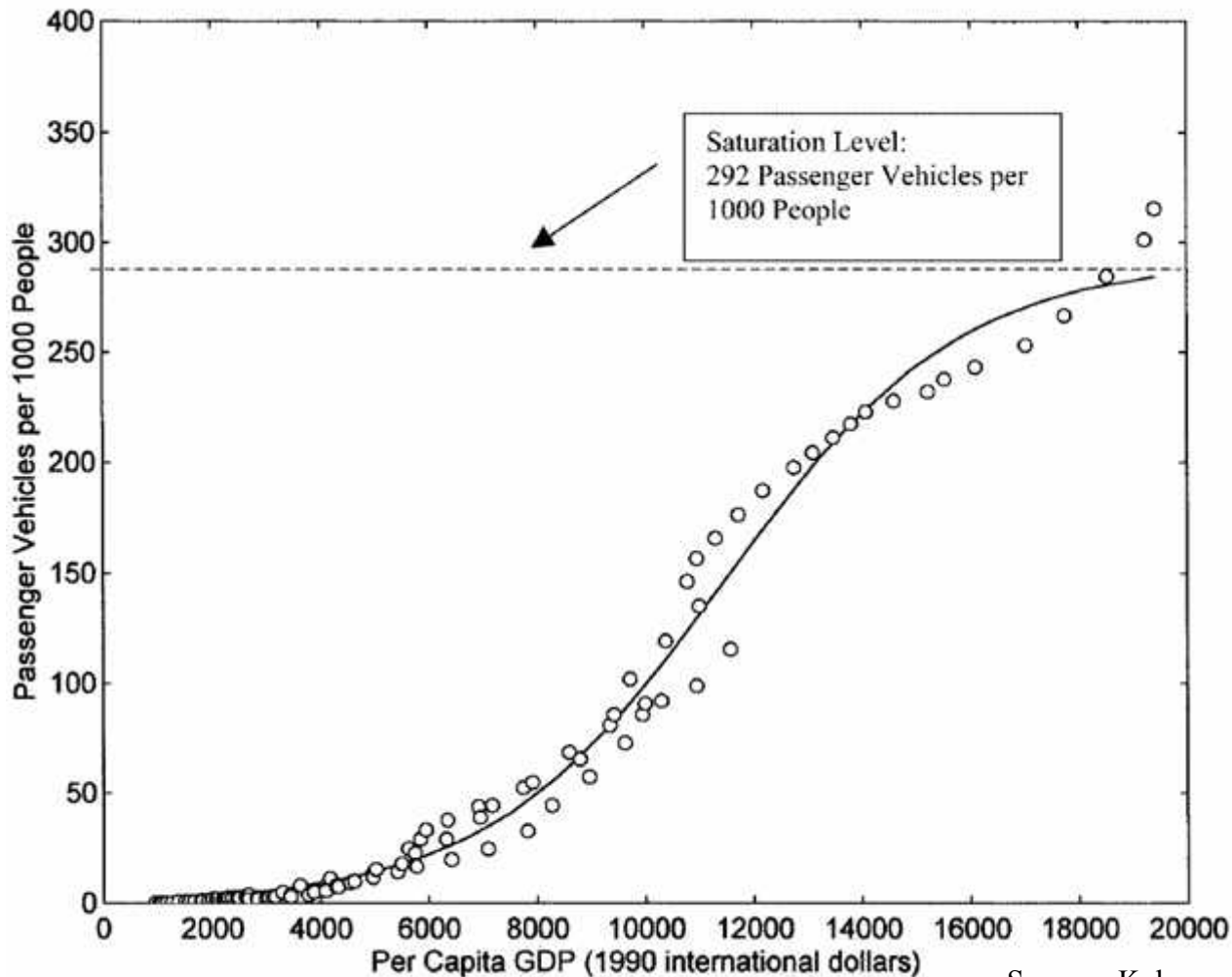
- Simulation / optimization, technology descriptive
- Useful for selecting fuel and technology choices
- e.g., Least-Cost optimization models, MARKAL, MESSAGE, NEMS

- **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*

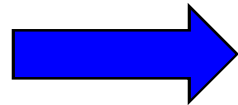
Estimating Market Saturation of Passenger Vehicle Ownership



Source: Kobos

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

(4) H₂O Treatment & Use



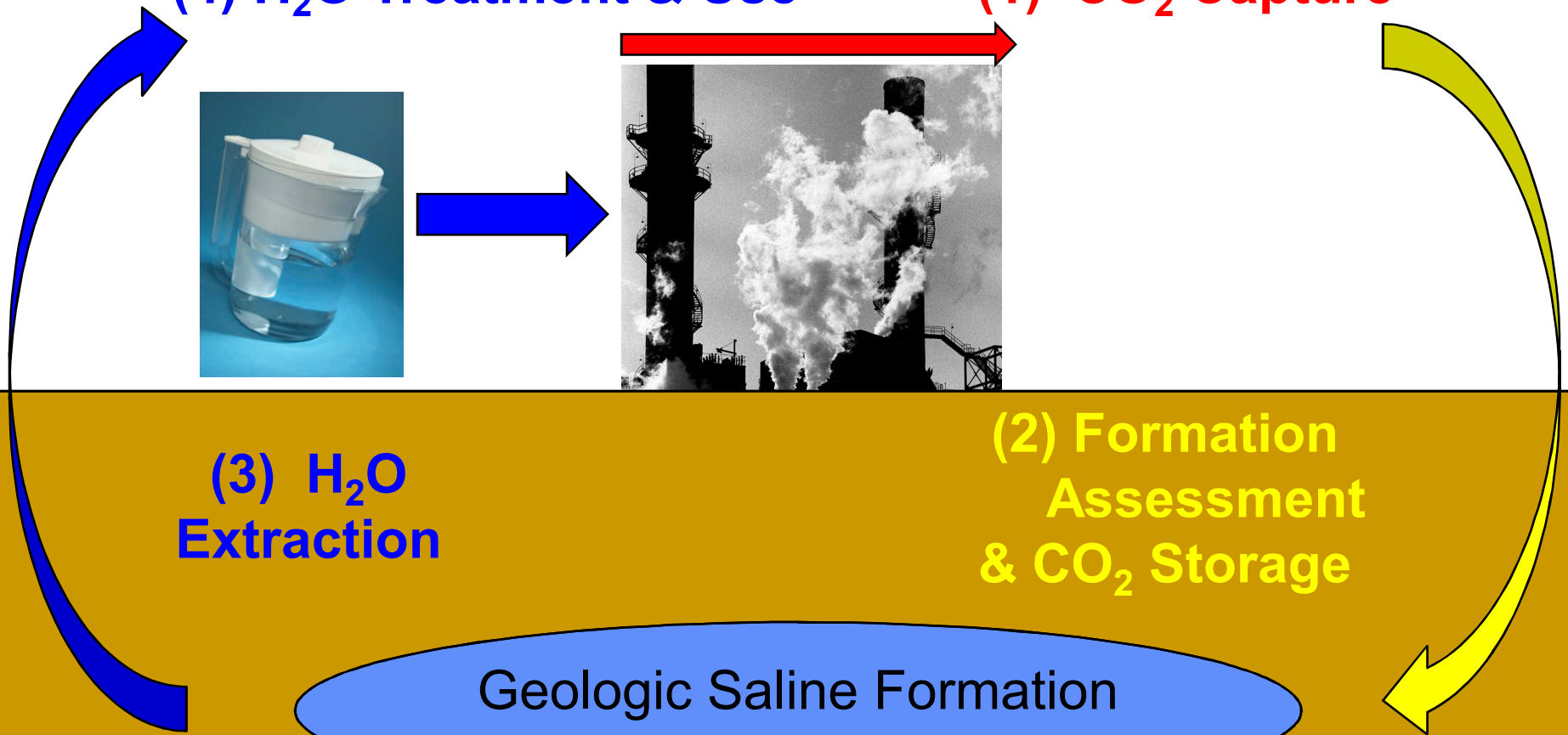
(1) CO₂ Capture



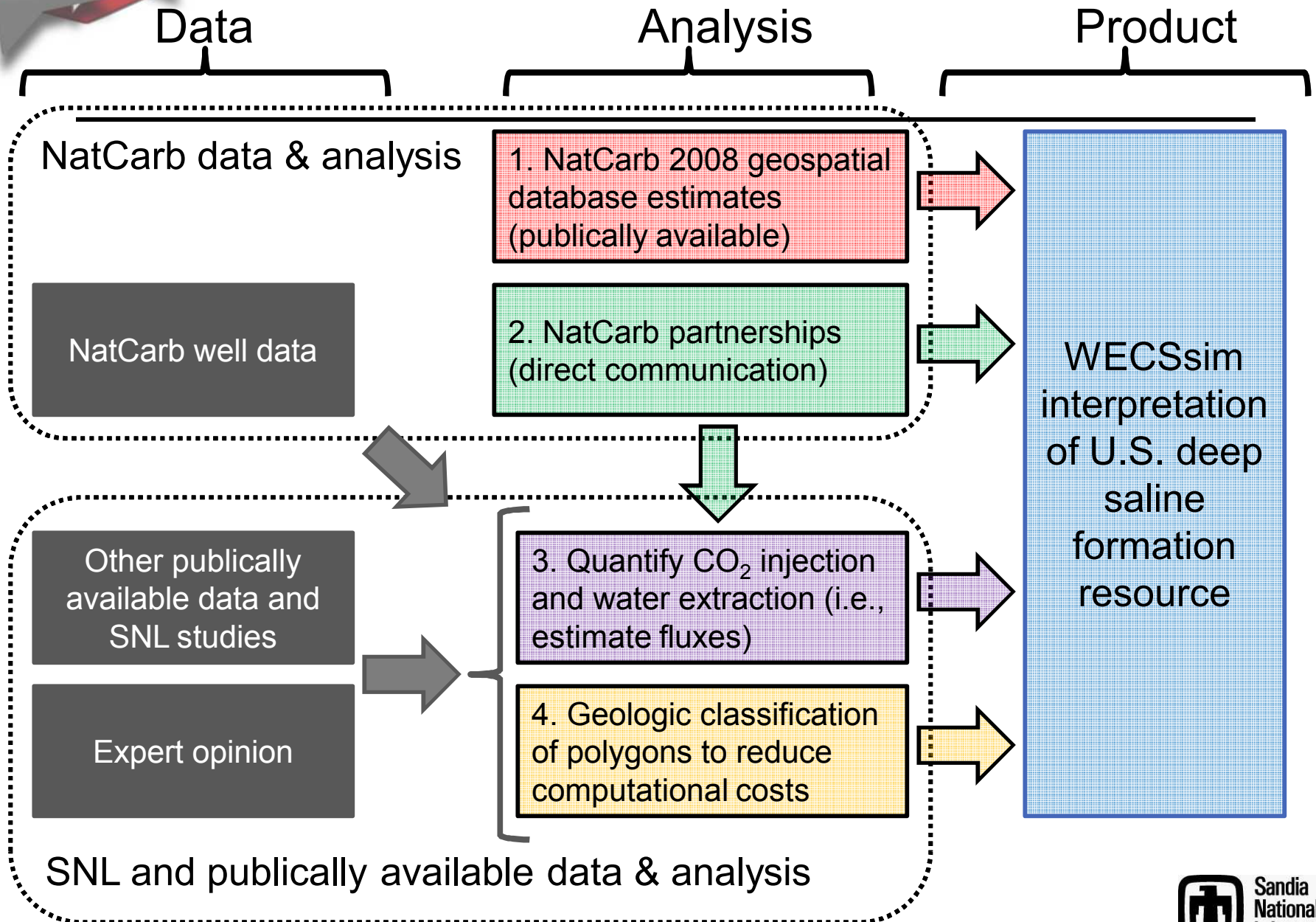
**(2) Formation
Assessment
& CO₂ Storage**

**(3) H₂O
Extraction**

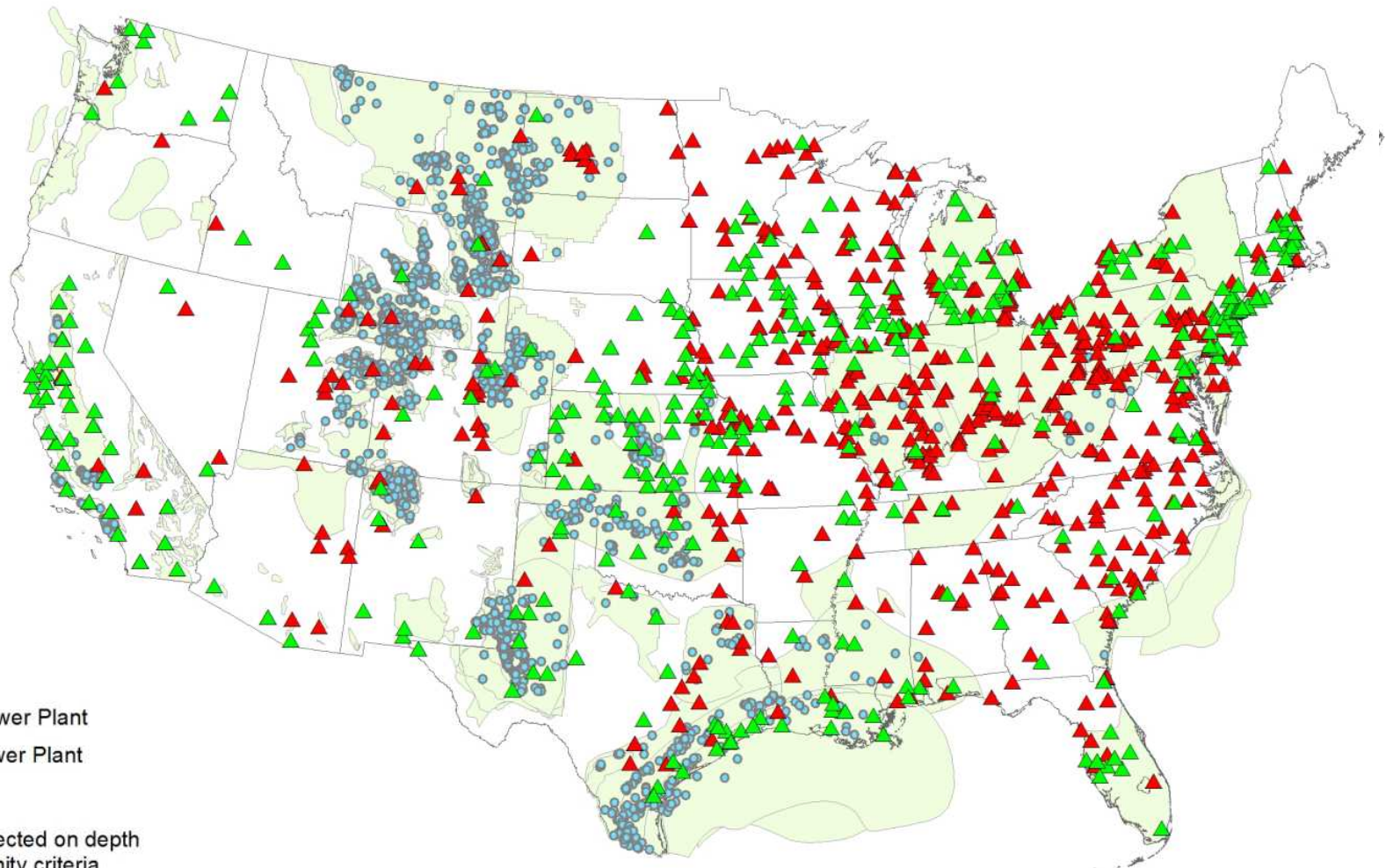
Geologic Saline Formation



Assessing U.S. deep saline formations



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



Legend

▲ Coal Power Plant

▲ Gas Power Plant

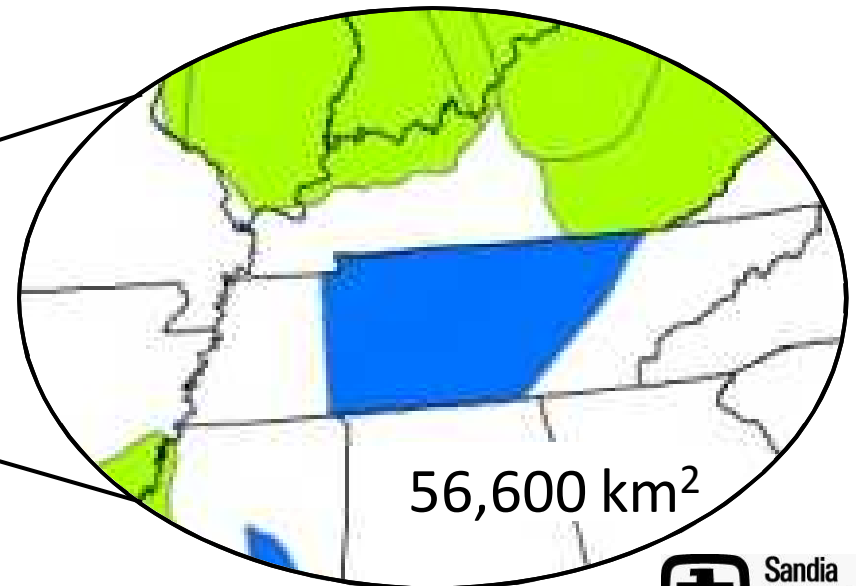
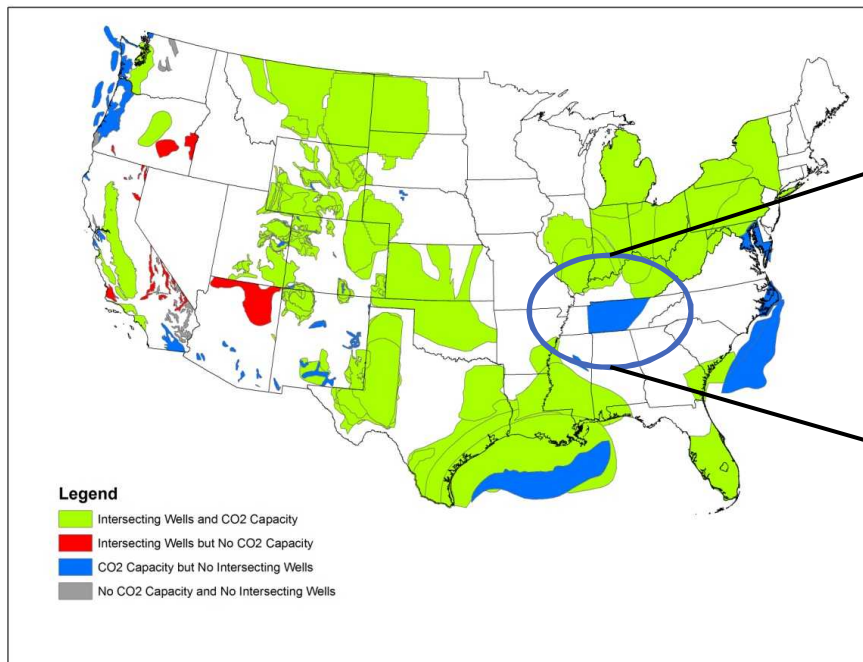
● Well

● 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

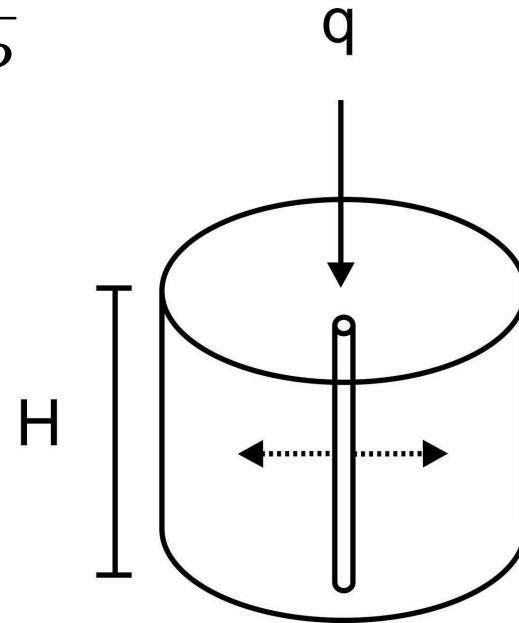
I well injectivity index;
measure of the “ease”
of injecting CO₂ into
the well

q volumetric flow rate

ΔP the pressure gradient

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

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

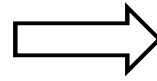


Reservoir Volume

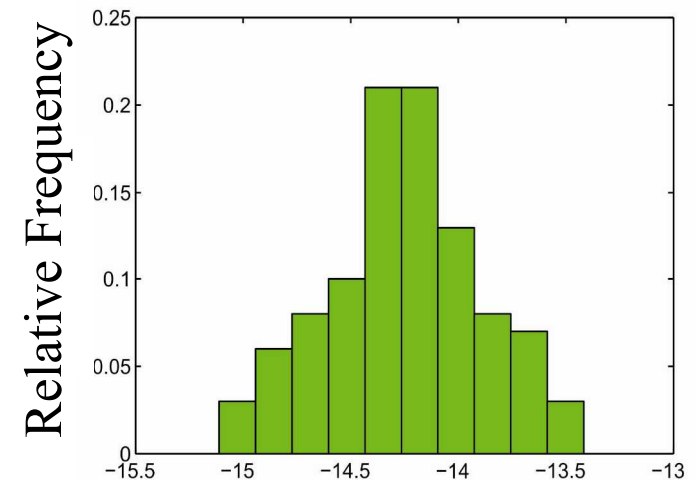
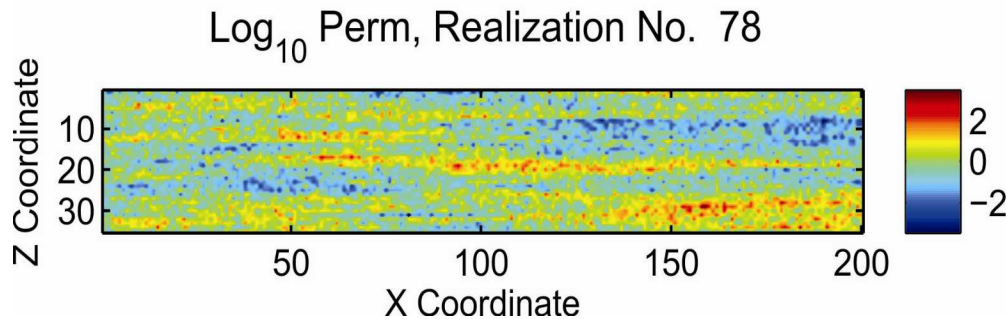
Radial flow from the
well

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



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

Power Plant

Carbon Capture

Carbon Sequestration

Extracted Water

Power Costs

Selected Sequestration Formation

Partnership	Basin Name	Formation Name
SECARB	Gulf Coast	Eocene Sand

☐ Model Default: SECARB

☒ Custom: SE_TG_TUS (changeable with dropdown)

☐ SECARB

☐ Tuscaloosa Group

☐ Tuscaloosa Group

Locations of Formation & Power Plant

Formation Centroid Location

	Latitude	Longitude
Default	31°41'3.48"	-89°53'54.96"
Custom (changeable)	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

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

Formation Footprint Area

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

Maximum distance power plant to default formation

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

50 100 150

50 mi

Formation Footprint Area

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

Input

Output

Distance from source to sink (at the flow line): 0.2 mi
Sequestration depth: 3,300 ft
Steady state temperature at sequestration depth: 55.6 °C
Steady state pressure at sequestration depth: 165.2 atm
Steady state density of CO₂ in sequestration formation: 894 kg/m³
Selected life of sequestration formation for selected source: 47,000 yr
Number of sequestration (injection) wells needed: 15
Total rate of sequestration: 0.42 km³/yr
Levelized cost of CO₂ transport and sequestration: 0.05 cents/kWh

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Partnership	Basin Name	Formation Name
SECARB	Gulf Coast	Eocene Sand

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☐ SECARB

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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 %	



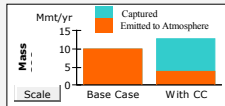
Power Plant Summary (Power Plant tab for details or to change values.)

Power Plant Type	Pulverized coal subcritical	Power Plant Location
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



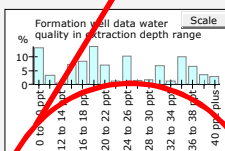
Carbon Sequestration (CS) Summary (Carbon Sequestration tab for details or to change.)

CO2 To Be Sequestered	8.9 Mmt/yr	Target CO2 Sequestration Location
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	



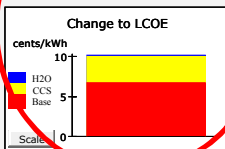
Extracted Water Summary (Extracted Water tab for details or to change values.)

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



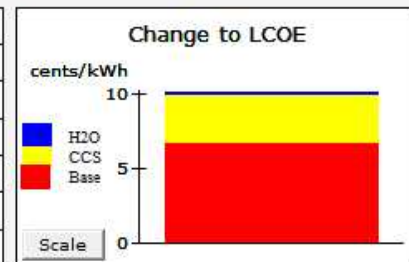
Power Costs Summary (2010 \$) (Power Costs tab for details or to change values.)

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
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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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Power Plant

Carbon Capture

Carbon Sequestration

Extracted Water

Power Costs

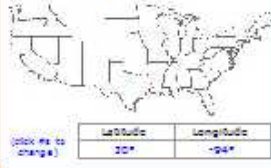
Summary

Power Plant Specs:

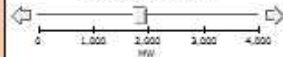
Power Plant Type

- ☐ Pulverised coal subcritical
- ☐ Pulverised coal supercritical
- ☐ Integrated gasification combined cycle
- ☐ Natural gas turbine
- ☐ Natural gas combined cycle

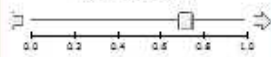
Power Plant Location



Installed Capacity



Capacity Factor



CO2 Production Rate

- ☐ Use default: 1,900 lbs/MWh
- ☐ Use custom: 2,200 lbs/MWh (click # to change)

Expected Year Online and Offline

	Starting	End Yr
<input type="radio"/> Existing plant	NA	2040
<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 type="radio"/> Use default	670 gal/MWh	520 gal/MWh
<input type="radio"/> Use custom (click # to change)	670 gal/MWh	520 gal/MWh

Base Levelized Cost of Electricity (LCOE)

	Total	Fuel Costs	Cooling	All Other	\$ Year:
<input 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

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

Cooling Technology

- ☐ Once through
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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)

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Defaults based on Exhibits ES-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

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.

Power plant generated carbon sequestration in saline formations

a dynamic analysis tool

Summary

Power Plant

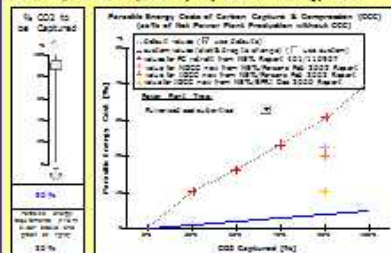
Carbon Capture

Carbon Sequestration

Extracted Water

Power Costs

Carbon capture and compression (CCC) amount and energy needs:



Make-up power characteristics:

Value: Net Power	Value: Net CO2 Capture	Value: Net CO2 Sequestration
Base Case: 1000 MW	Base Case: 1000 MW	Base Case: 1000 MW
Value: Net CO2	Value: Net CO2 Sequestration	Value: Net CO2 Sequestration
Base Case: 1000 MW	Base Case: 1000 MW	Base Case: 1000 MW

Additional H2O needs due to CO2 capture & compression (CCC) processes:

Value: H2O needed for CO2 capture	Value: H2O needed for CO2 compression
Base Case: 1000 MGD	Base Case: 1000 MGD
Value: H2O needed for CO2 capture	Value: H2O needed for CO2 compression
Base Case: 1000 MGD	Base Case: 1000 MGD

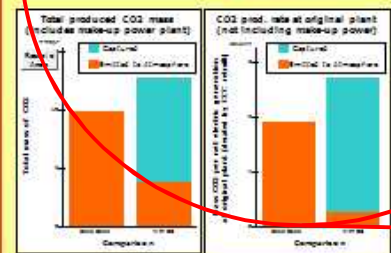
Power needs for CCC: 30 % of base net power
= 3.4 TWh/yr

Mass CO2 generated by original plant: 9.9 Mmt/yr
Mass CO2 generated at make-up plant: 2.8 Mmt/yr
Total CO2 generated: 12.7 Mmt/yr

Mass CO2 captured at original plant: 8.9 Mmt/yr
Mass CO2 captured at make-up plant: 0 Mmt/yr
Total CO2 captured: 8.9 Mmt/yr

Water withdrawal at original plant for CCC: 2.7 billion gal/yr
Water withdrawal at make-up plant: 1.8 billion gal/yr
Total new water withdrawals for CCC: 12.5 MGD

= 58 % increase



Output

Power needs for CCC: 30 % of base net power

= 3.4 TWh/yr

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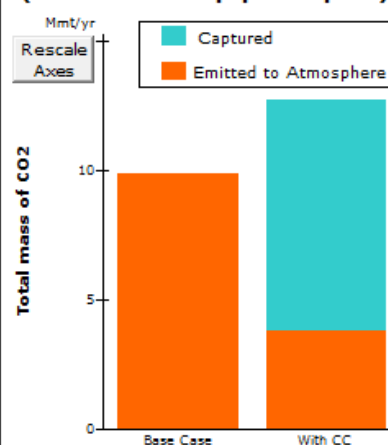
Water withdrawal at original plant for CCC: 2.7 billion gal/yr

Water withdrawal at make-up plant: 1.8 billion gal/yr

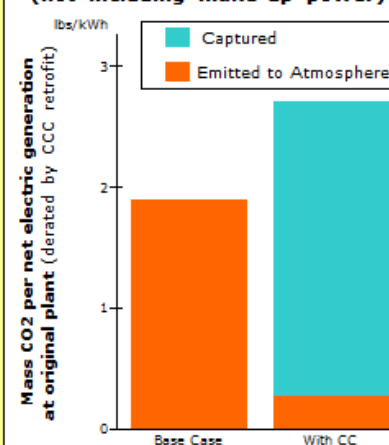
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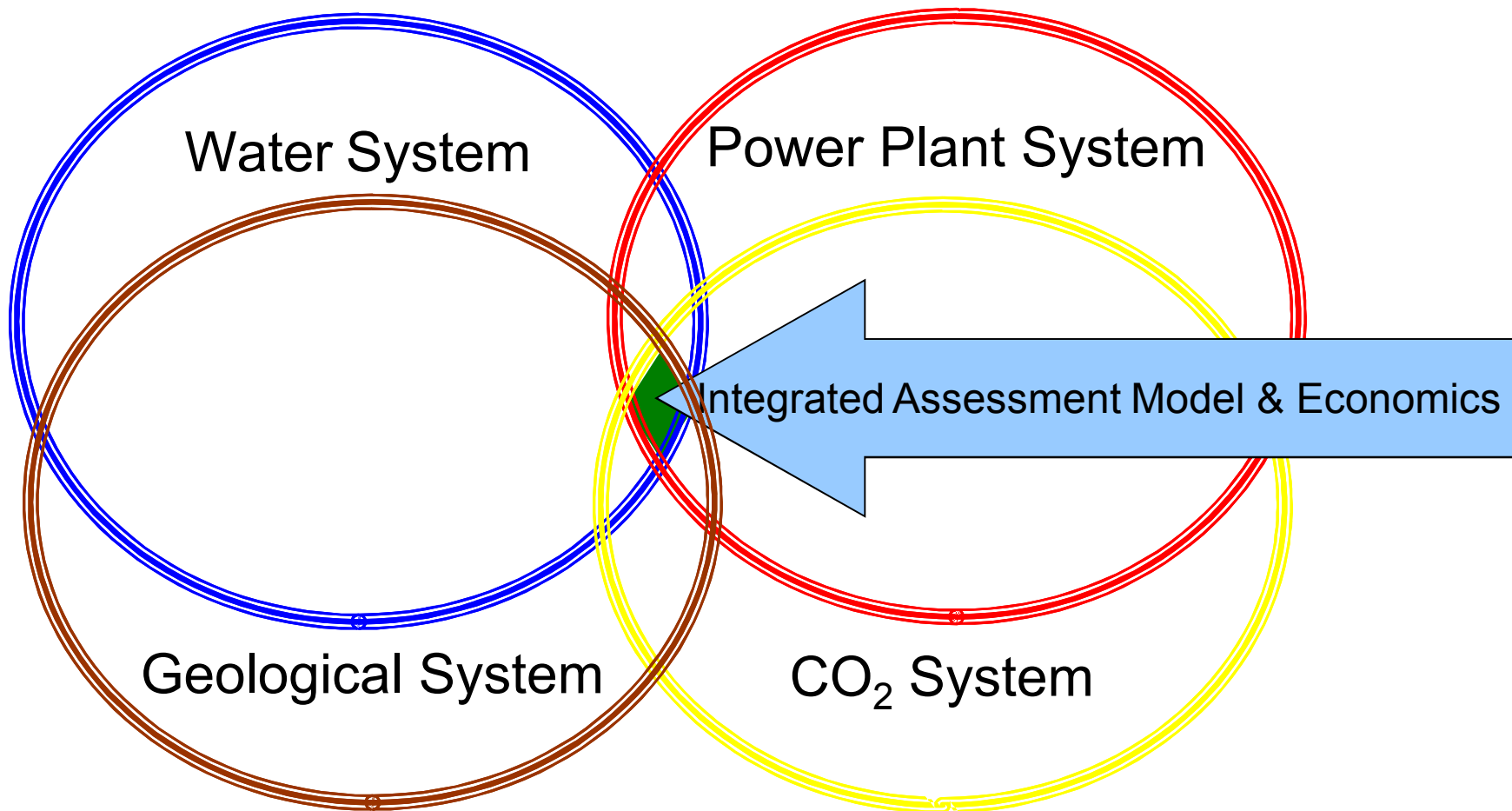
Total produced CO2 mass (includes make-up power plant)



CO2 prod. rate at original plant (not including make-up power)



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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