SAND2012-1094P

The Water, Energy and Carbon Sequestration Simulation Model (WECSsim)

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Jason E. Heath, Geoff T. Klise, Thomas A. Dewers, Sean A. McKenna, Len Malczynski, David J. Borns, Karen A. Gutierrez
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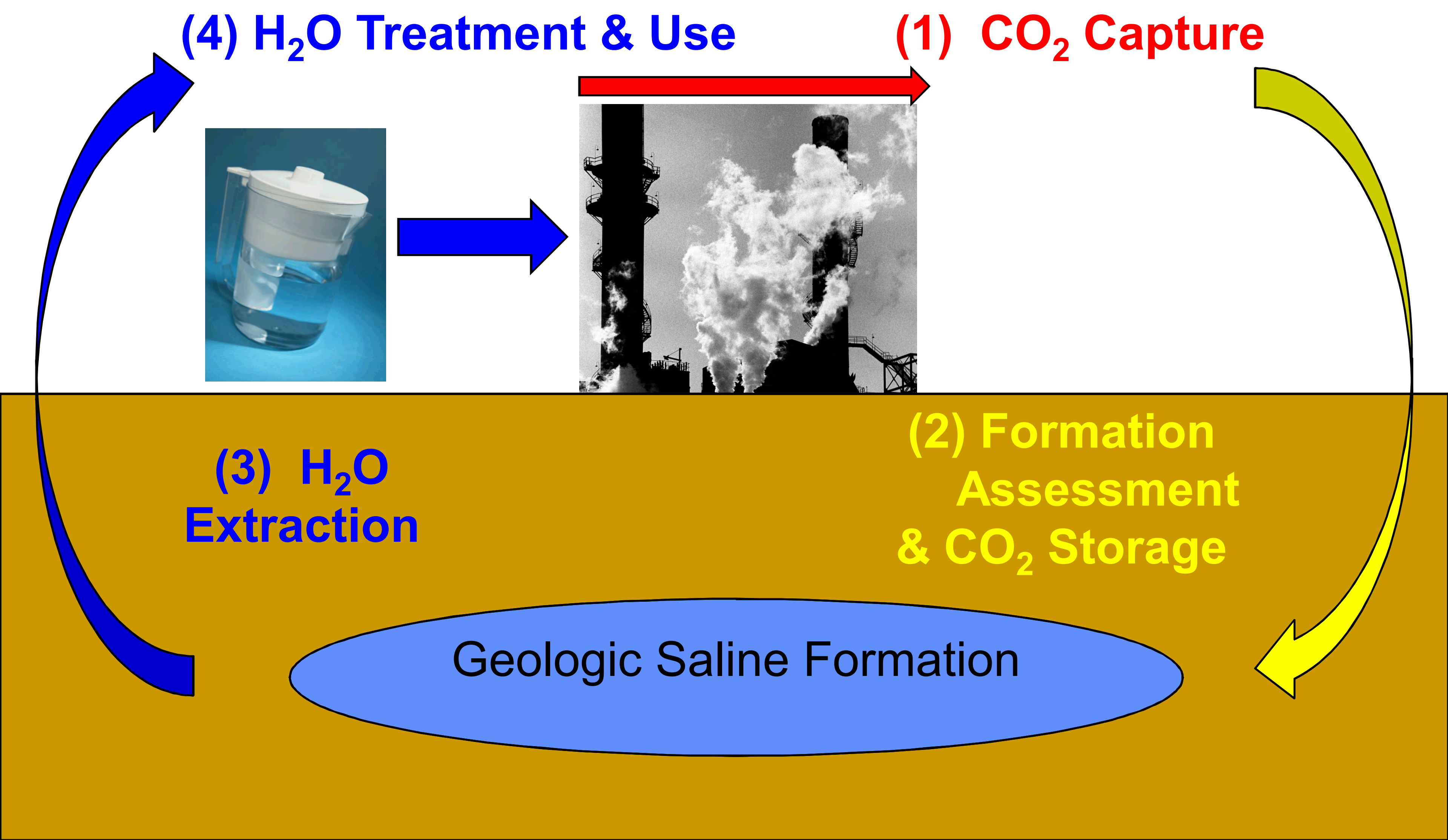
and thanks to
Andrea McNemar
National Energy Technology Laboratory

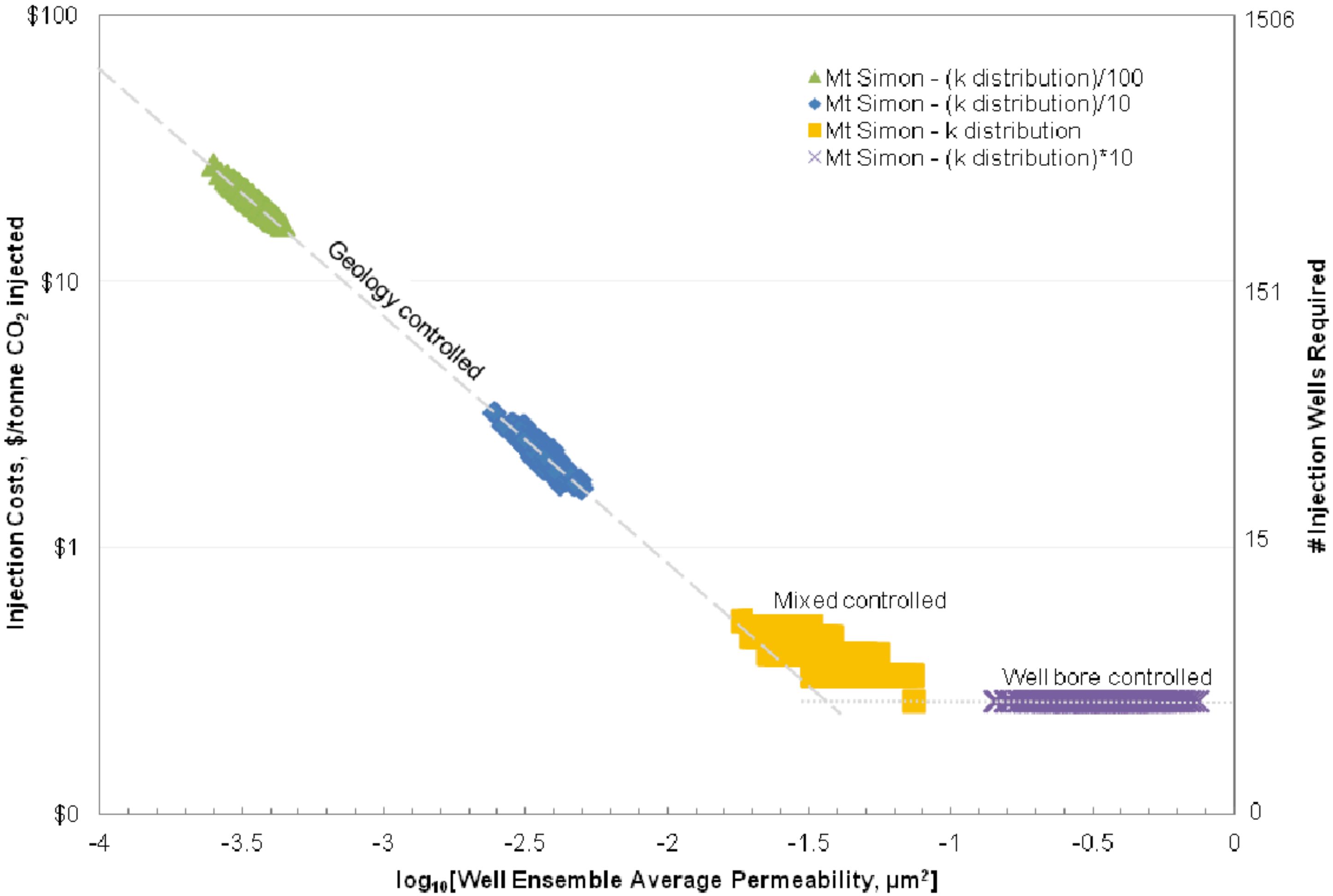
February 15, 2012

Acknowledgements: This work is developing under the funding and support of the National Energy Technology Laboratory.

Water, Energy and CO_2 Sequestration (WECS) Model:



Phase V:
Permeability & Engineered Constraints Drive Well Costs



Source: Heath, J.E., Kobos, P.H., Roach, J.D., Dewers, T.A. and S.A. McKenna, "Geologic Heterogeneity and Economic Uncertainty of Subsurface Carbon Dioxide Storage," SPE Economics & Management Journal, *in press*.

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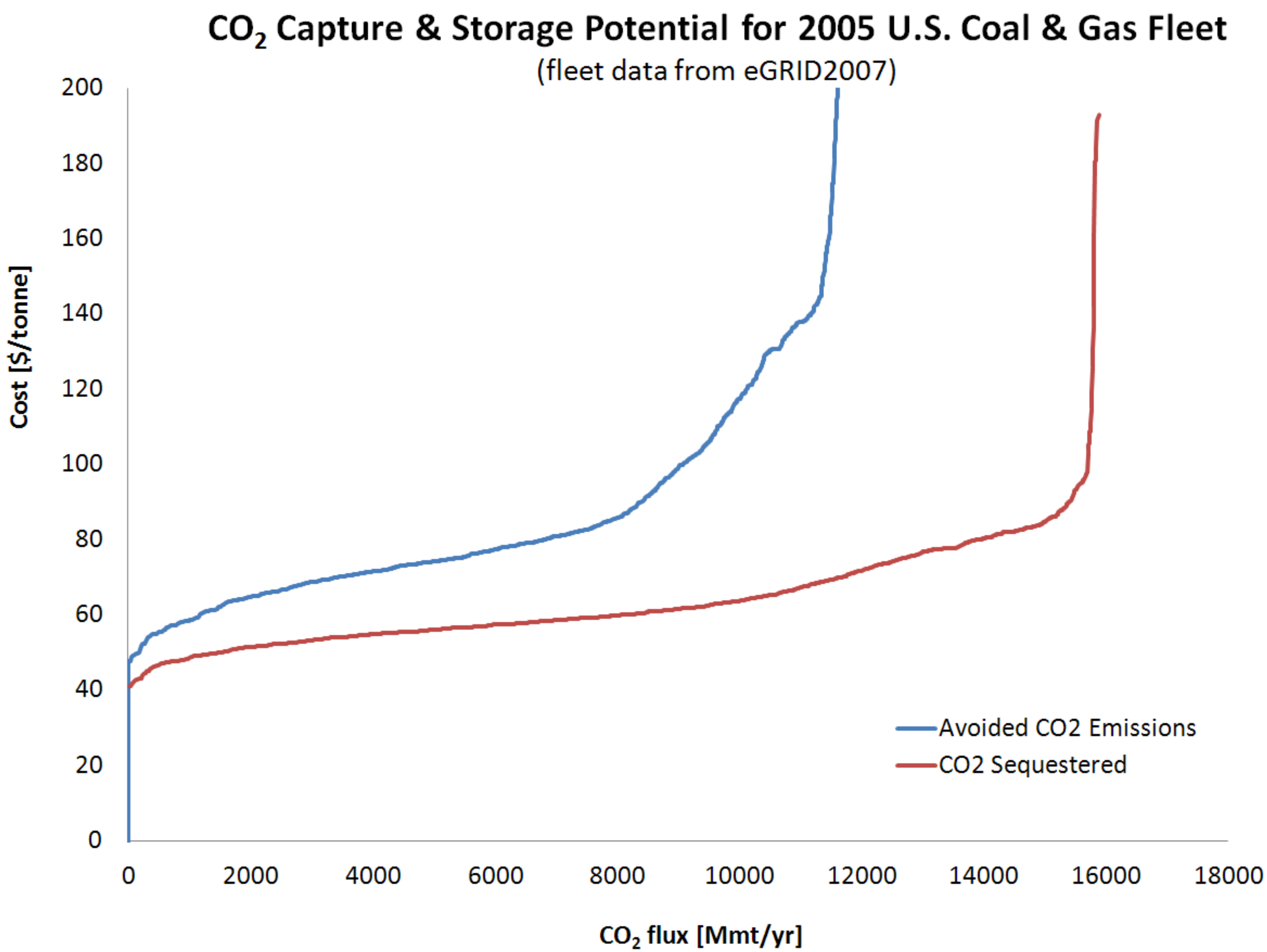
Working Results:
Developing a National, Dynamic CO_2 Storage Supply Curve



Project Timeline & Goals

Timeline

2007

- Completed Phase I: Developed a Test Case Model (WECS)

2008

- Completed Phase II: Additional TOUGH2 Analysis

2009

- Completed Phase III: Developed a single power plant to any saline formation sink in the U.S. systems calculator

2010

- Phase IV: Expanding the role of uncertainty in the model
  - Several order of magnitude variation in key geologic parameter (permeability)
  - Incorporating uncertainties into costs

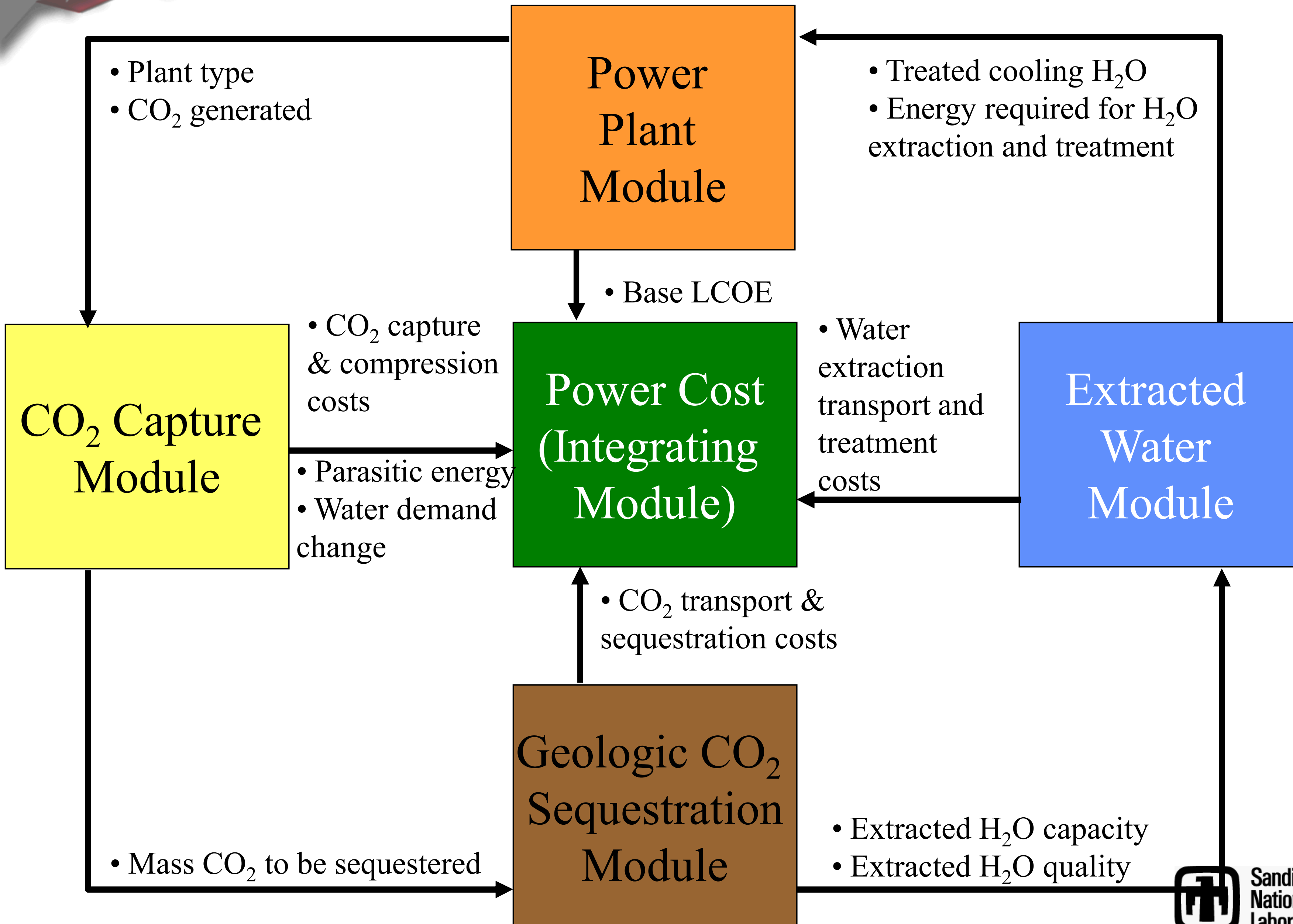
2011

- **Phase V:**

2012

  - Refining permeability, porosity representation in WECSsim
  - Finalizing WECSsim Interface (Spring/Summer)
  - Develop WECSsim User's manual (Summer/Fall)

WECSsim Modular Structure



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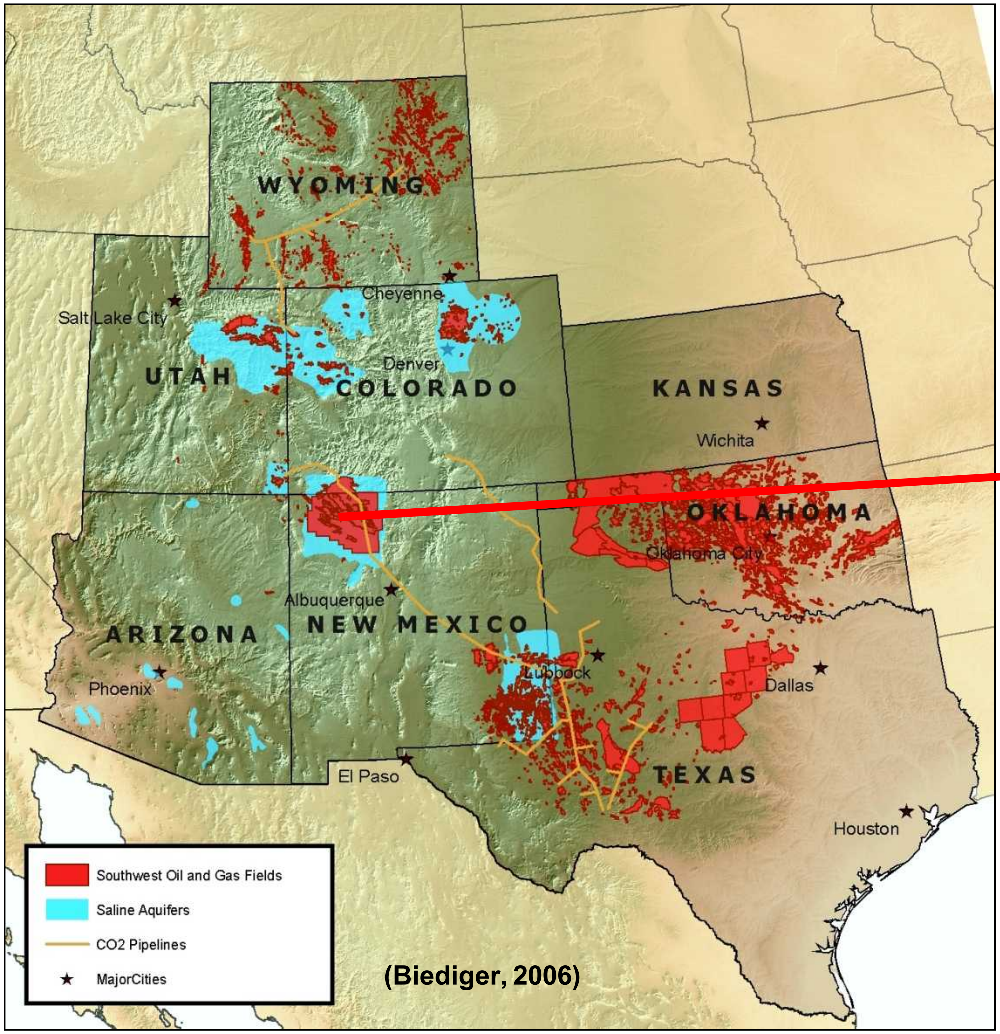
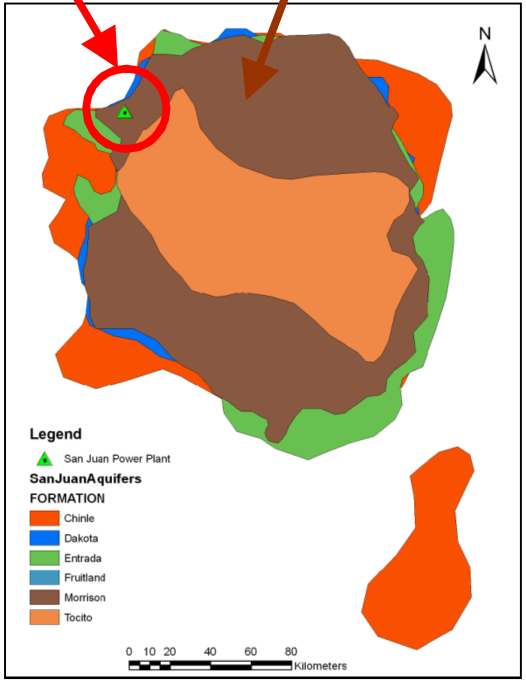
Phase I:
The San Juan Power Plant and Morrison Formation



(Biediger, 2006)

San Juan Power Plant

Morrison Formation



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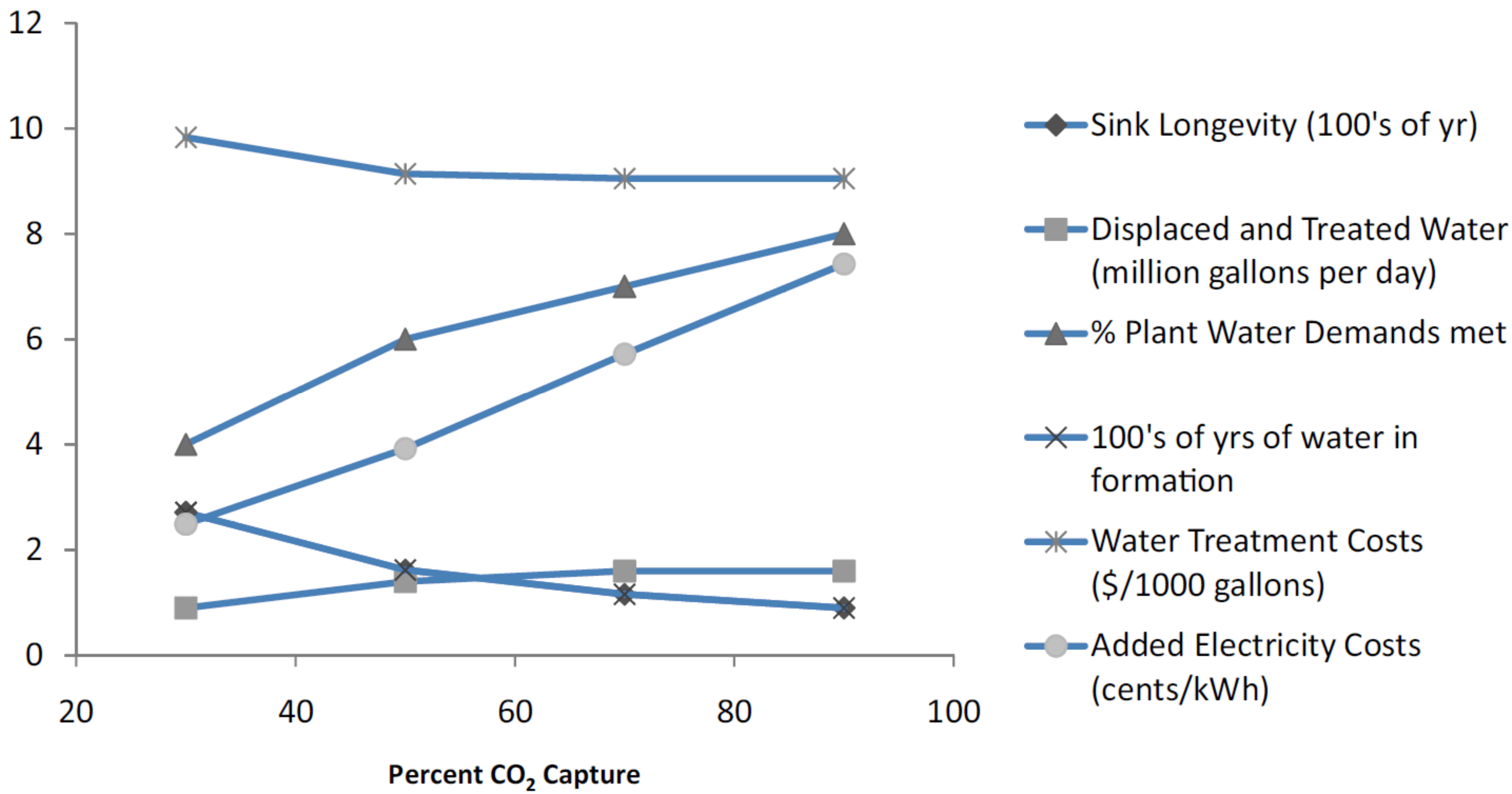
Phase II & III:

Single Power Plant to Single Geologic Storage Site



Source: Kobos et al., 2011, *International Journal of Greenhouse Gas Control*, 5, 899-910.

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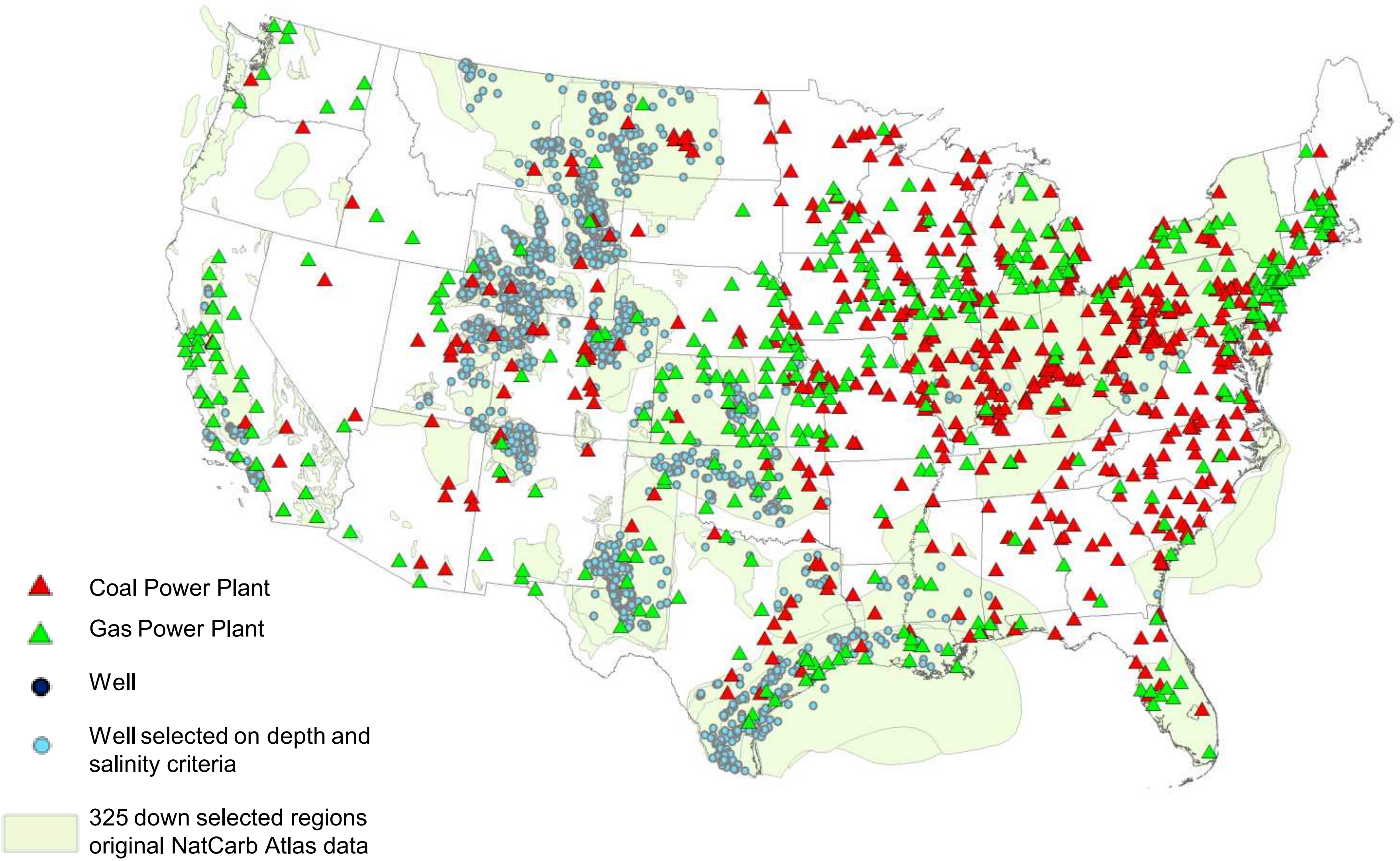
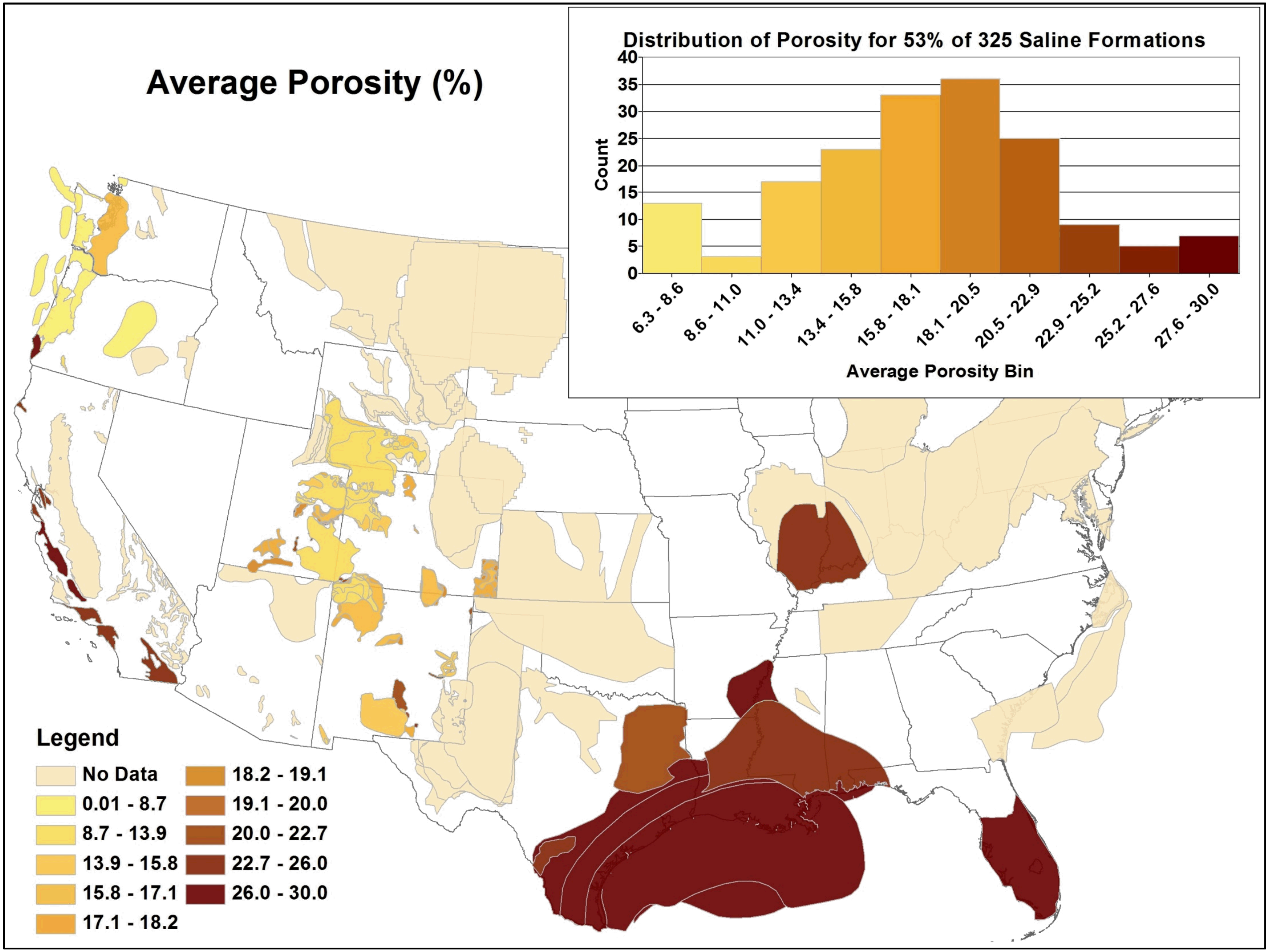
Phase III & IV:
Geological CO_2 Storage Database Challenges



Phase V:
Distribution of *Porosity*, & other characteristics



Phase V:
Data Challenge in the Context of Cost

Data Challenge	Required to Calculate	Result
Formation Permeability	→	Injection Rates per Well
Injection Rates Per Well	→	Number of Wells per Power Plant & CO_2 Sink Combo.
Number of Wells	→	Cost of Infrastructure & Well Spacing
Costs & Well Spacing	→	Manage Communication between Wells
Communication Between Wells	→	Calculate the Levelized Lifetime Cost (and years) for the CO_2 Sink & H_2O resource

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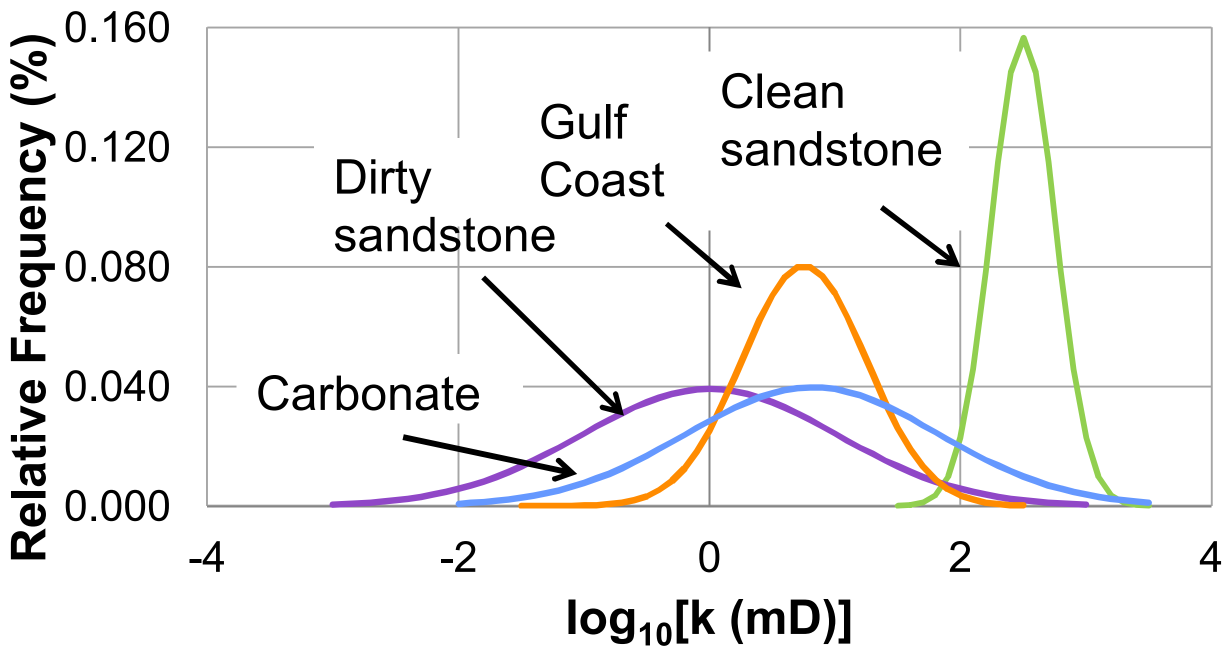
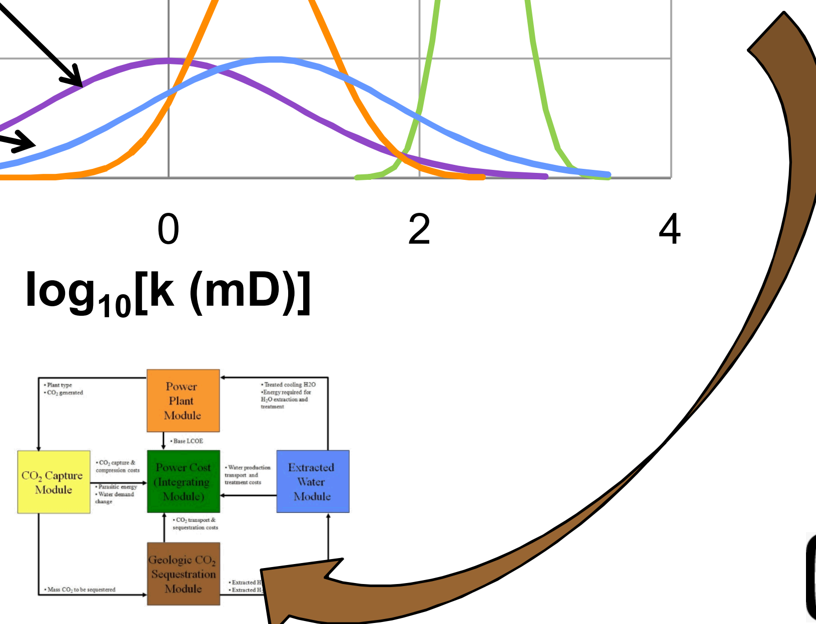
Phase V:
Expanding the ‘Geology Controlled’ (Permeability) factor to Cost Relationship across all Sinks

Injectivity equation: permeability sampled from 4 Rock Types





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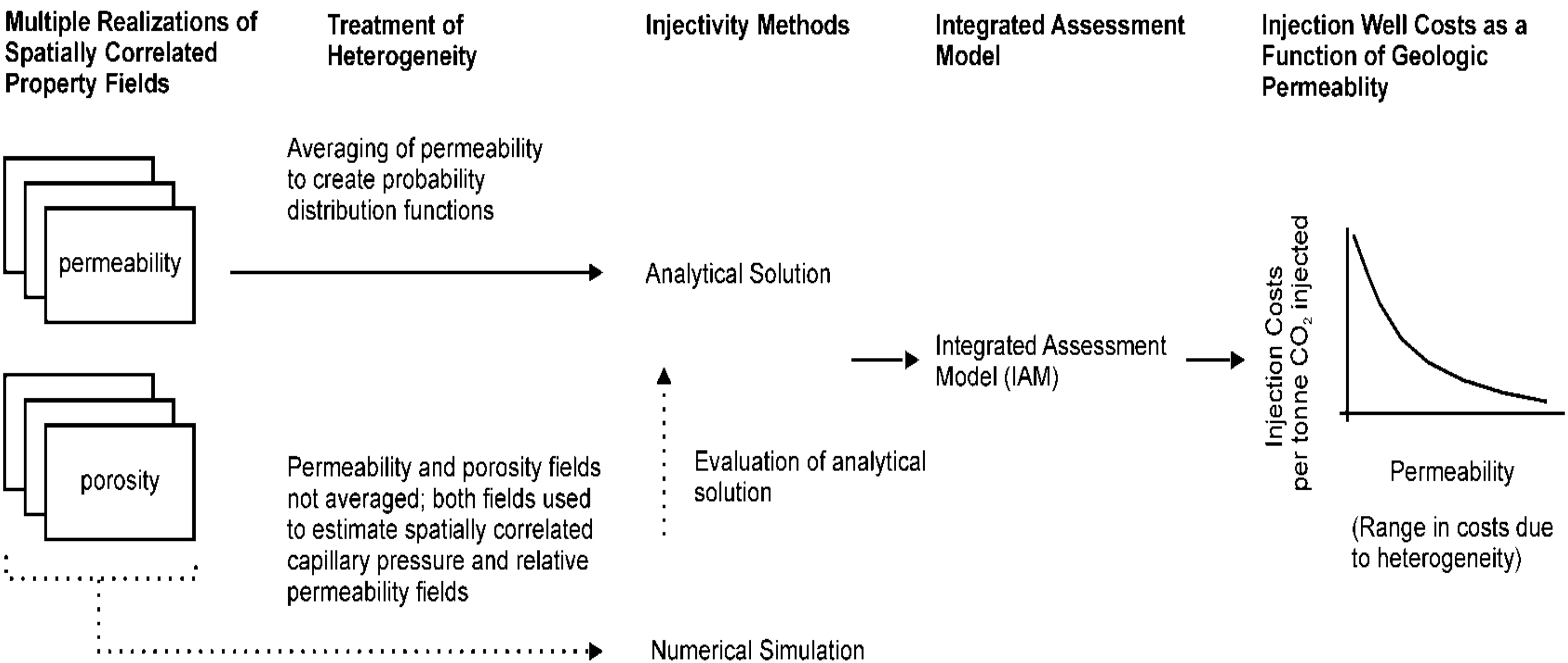
Methods behind the Permeability-to-Cost Analysis



Source: Heath, J.E., Kobos, P.H., Roach, J.D., Dewers, T.A. and S.A. McKenna, "Geologic Heterogeneity and Economic Uncertainty of Subsurface Carbon Dioxide Storage," SPE Economics & Management Journal, *in press*.

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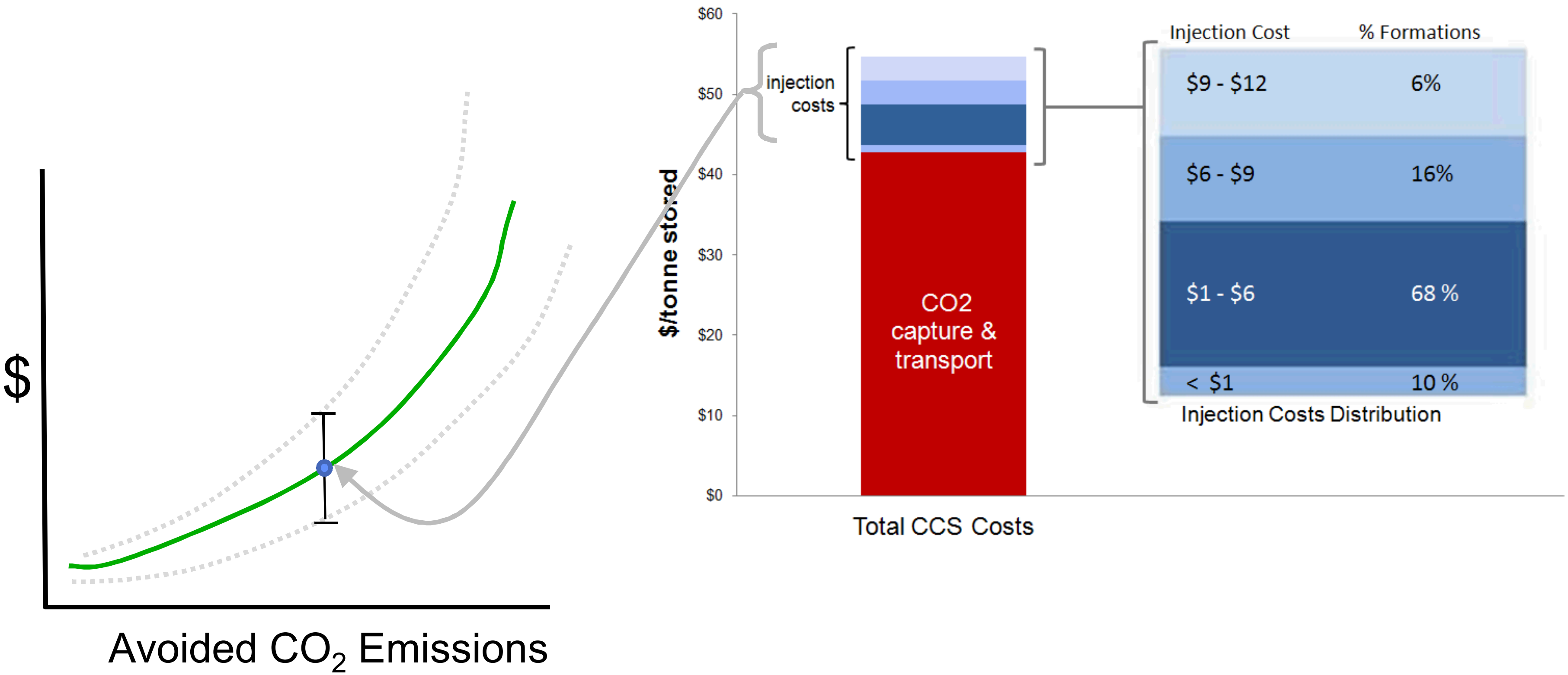
WECSsim Results:
Similar Full Economic Analysis Underway



Note: Illustrative Example at this time

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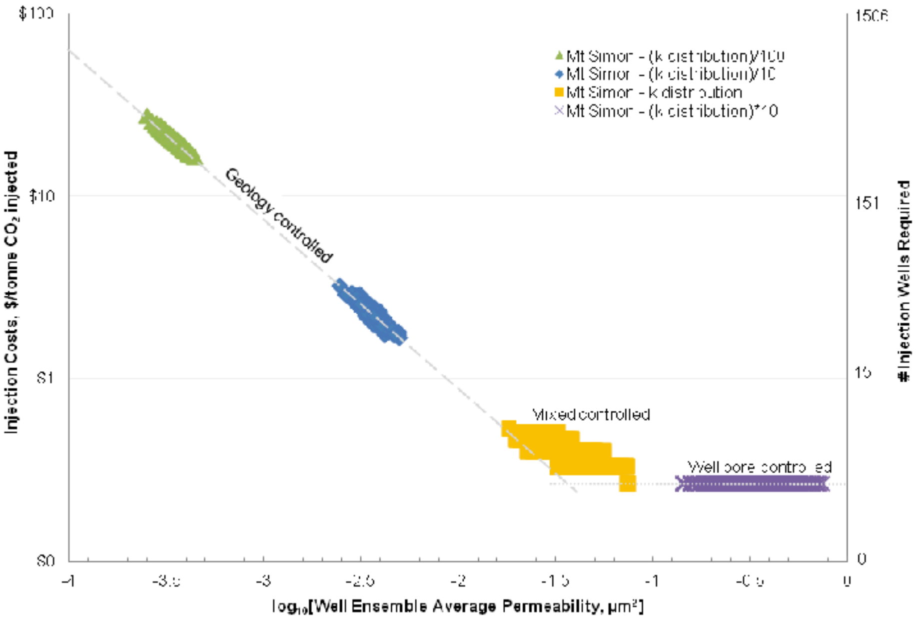
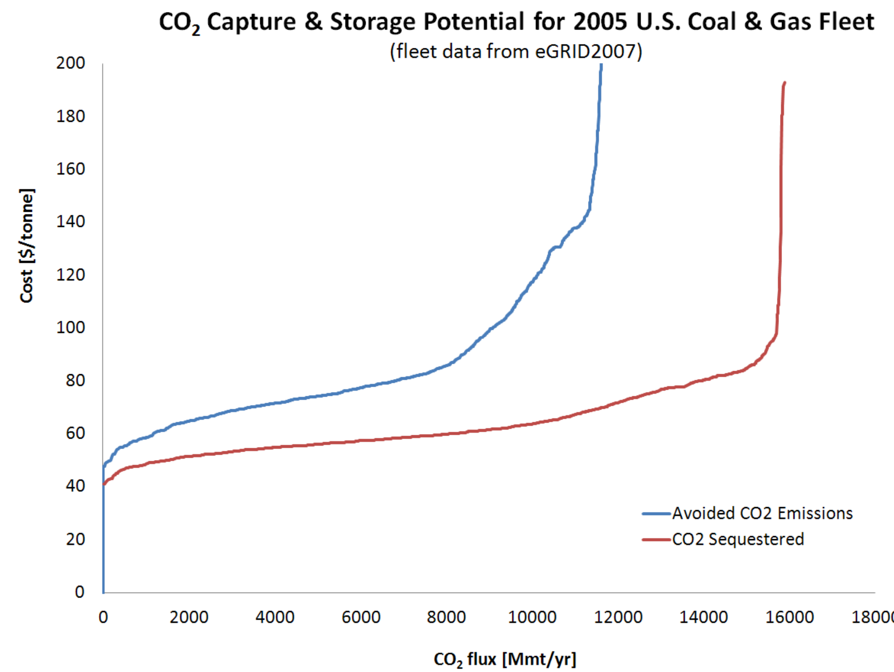
Summary:

Phase V identifying costs, capacity, and siting criteria





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Phase V:
Other notable progress

- **WECSsim**
  - Substantial interface ease-of-use work
  - Improved usability: single power plant, or national storage supply curve
  - Model dissemination strategy update
- **Output:**
  - Published manuscript in SPE Journal of Economics & Management
  - Poster accepted for upcoming 11th Annual conference on CCUS
  - Finalizing manuscript documenting data assessment of NatCarb information

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Key Messages

Framework for National Level Assessment

- Cost of CCS from any U.S. fossil fuel power plant to any deep saline formation
- Site-specific nature of geologic data challenge

Impact of Geologic Uncertainty on Costs

- Low injectivity requires more injection wells and therefore higher costs
- High permeability reservoirs with low injection costs (< $1/tonne) represent < ~10% of the 325 formations
- Scale-up challenge

Model Discussions

The Water, Energy and Carbon Sequestration Simulation Model (WECSsim)

Ongoing and Future Work

National Level Supply Assessment

- i.e., "How much low-cost CO_2 storage exists in the U.S.?"

Spatial distribution of CO_2 sources to sinks

- i.e., "Are the high quality sinks accessible to large sources?"
- "How will competition for storage sinks change the national supply curve?"

CO_2 injectivity-brine extractivity and heterogeneity

- i.e., "How do injection rates improve with brine extraction?"

Future Opportunities:
Ideas to Enhance WECSsim

1.1 Enhanced Oil Recovery in WECSsim

1.2 CO_2 Storage Competition Over Time

1.3 Water Treatment Technologies for Carbon Capture, Use and Storage (CCUS)

1.4 Expanding the WECSsim Model Interface to be fully Web-Based.

1.5 To Extract or Not: Tradeoff Analysis for Treated Saline Formation Waters

1.6 Updating WECSsim to use NatCarb 2012+

For Further Information:

Heath, J.E., Kobos, P.H., Roach, J.D., Dewers, T.A. and S.A. McKenna, "Geologic Heterogeneity and Economic Uncertainty of Subsurface Carbon Dioxide Storage," SPE Economics & Management Journal, *in press.*

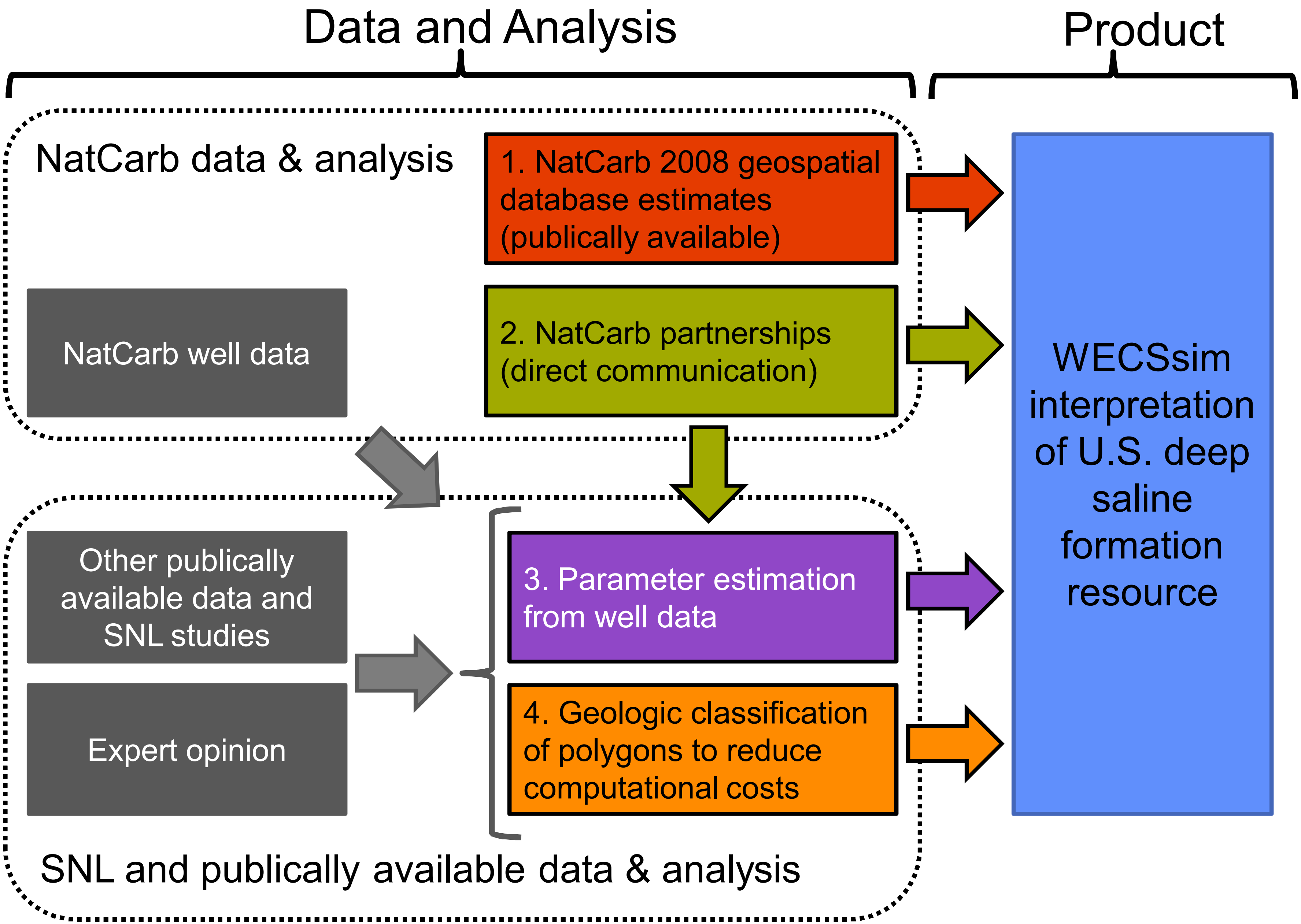
Kobos, P.H., Cappelle, M.A., Krumhansl, J.L., Dewers, T.A., McNemar, A., Borns, D.J., 2011. Combing power plant water needs and carbon dioxide storage using saline formations: Implications for carbon dioxide and water management policies. *International Journal of Greenhouse Gas Control*, 5, 899-910.

The Water, Energy and Carbon Sequestration Simulation Model (WECSsim)

Thank you.

Backup Slides

Assessing U.S. deep saline formations



Limited Saline Formation Data

Data availability by source for 325 polygons derived from NatCarb 2008

Data Source	CO_2 storage capacity	Area	Depth	Thickness	Porosity	Perm	TDS	Temp	Pressure
NatCarb 2008	42%	100%	0%	0%	0%	0%	0%	0%	0%
Partnerships	42%	100%	62%	64%	55%	0%	18%	44%	45%
Well records	NA	NA	70%[1]	70%[1]	0%	0%	70%[1]	100%[2]	NA
Geologic class	NA	NA	NA	NA	100%	100%	0%	NA	NA
No estimate	**16%** (52)	**0%** (0)	**14%**[3] (47)	**14%**[3] (47)	**0 %** (0)	**0 %** (0)	**14%**[3] (47)	**14%**[3] (47)	**14%**[3] (47)

Notes:

1. 30% of polygons (97 of 325) have no potentially intersecting wells associated with them from well databases used here.
2. Temperature calculated from depth and geothermal gradient. Geothermal gradient was developed spatially from publically available well records.
3. 14% of polygons (47 of 325) have no depth, thickness, or salinity information and no potentially intersecting wells.

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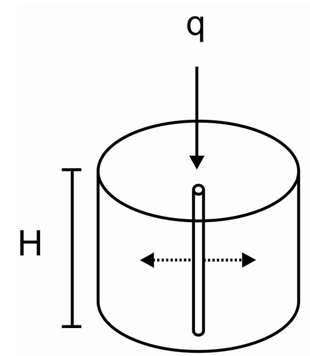
Multi-Well CO_2 Injection: With or without Brine Extraction

I well injectivity index; measure of the "ease" of CO_2 injection

q volumetric injection rate

ΔP the pressure gradient

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



Radial flow from the well

Options in WECSsim:

CO2 Injectivity Method

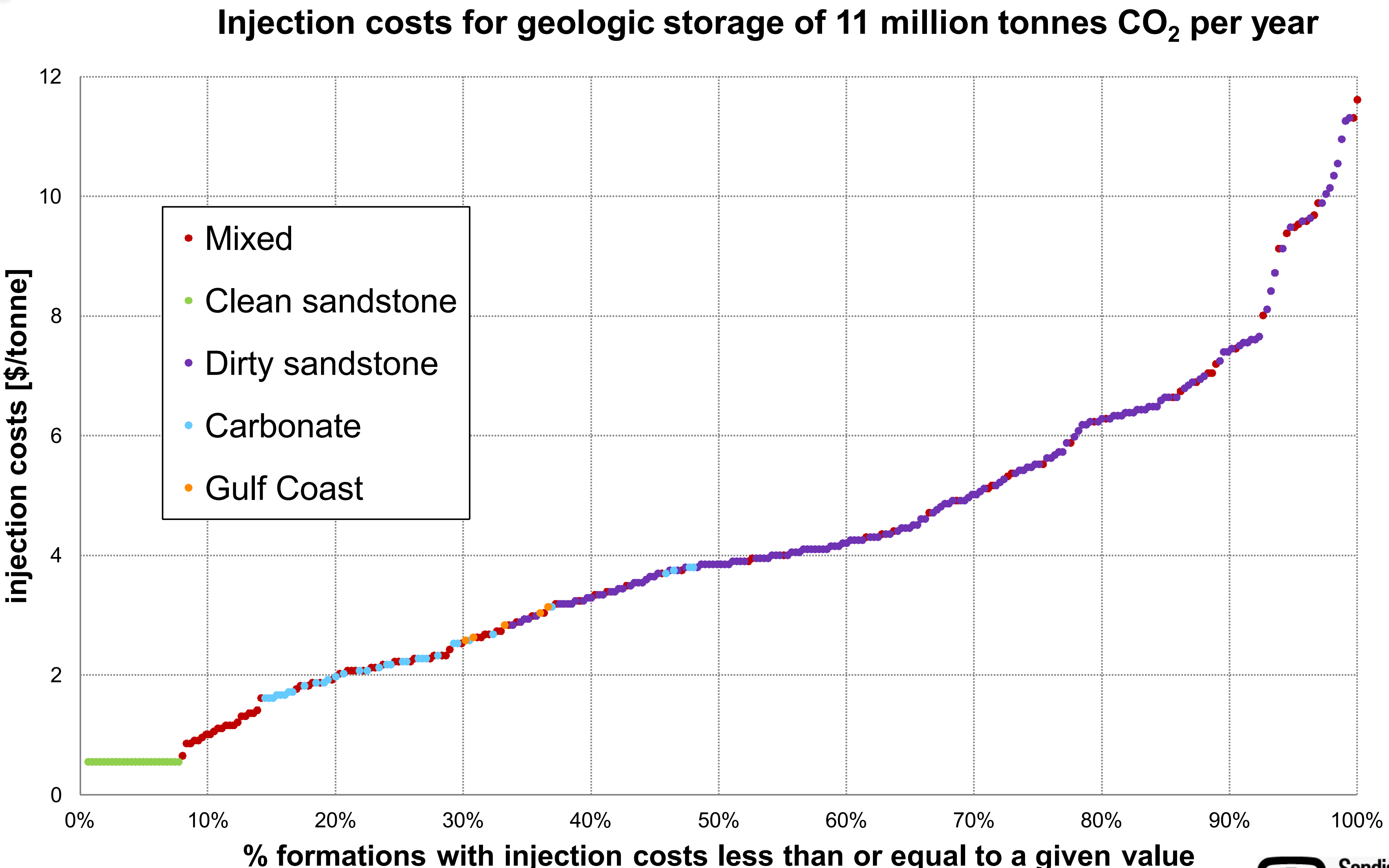
- Bryant & Lake, 2005
- Stauffer et al., 2007
- Eccles, 2011
- McCollum, 2006

No brine extraction

- Heath, 2011 — Brine extraction

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

The Next Step:
Working Towards a National Storage Supply Curve



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Productivity:
Output is more than Double the Required Deliverables

- **Project Deliverables, Reports (4+):**
  - Kobos, P.H., Roach, J.D., Klise, G.T., Krumhansl, J.L., Dewers, T.A., Heath, J, Dwyer, B.P., Borns, D.J. and A. McNemar, "Study of the Use of Saline Formations for Combined Thermoelectric Power Plant Water Needs and Carbon Sequestration at a Regional Scale: Phase III Report," SAND2011-5776P, Updated 8/2011.
  - Kobos, P.H., Krumhansl, J.L., Dewers, T.A., Klise, G.T., Dwyer, B.P., Tidwell, V.C., Kottenstette, R., Borns, D.J. and A. McNemar, "Thermoelectric Power Plant Water Demands Using Alternative Water Supplies: Power Demand Options in Regions of Water Stress and Future Carbon Management," SAND2011-5808P, Updated 8/2011.
  - Kobos, P.H., Krumhansl, J.L., Dewers, T.A., Cappelle, M.A., Heath, J.E., Dwyer, B.P., Borns, D.J. and A. McNemar, "Study of the Use of Deep Saline Formations for Combined Thermoelectric Power Plant Water Needs and Carbon Sequestration at a Regional-Scale: Phase II Report," SAND2010-8073P, 6/2010.
  - Kobos, P.H., Cappelle, M.A., Krumhansl, J.L., Borns, D.J., Hightower, M.M., and A. McNemar, "Study of the Use of Saline Aquifers for Combined Thermoelectric Power Plant Water Needs and Carbon Sequestration at a Regional-Scale: Phase I Report," SAND2008-4037, Updated 3/2010.
- **Journal Publications (3)**
  - Heath, J.E., Kobos, P.H., Roach, J.D., Dewers, T.A. and S.A. McKenna, "Geologic Heterogeneity and Economic Uncertainty of Subsurface Carbon Dioxide Storage," SPE Economics & Management Journal, in press.
  - Kobos, P.H., Cappelle, M.A., Krumhansl, J.L, Dewers, T.A., McNeamar, A. and D.J. Borns, 2011 "Combining power plant water needs and carbon dioxide storage using saline formations: Implications for carbon dioxide and water management policies," International Journal of Greenhouse Gas Control, Volume 5, Issue 4, July, pages 899 − 910.
- **Conference Proceedings, Papers (6+):**
  - Kobos, P.H., Roach, J.D., Heath, J.E., Dewers, T.A., McKenna, S.A., Klise, G.T., Krumhansl, J.L., Borns, D.J., Gutierrez, K.A. and A. McNemar, "Economic Uncertainty in Subsurface CO2 Storage: Geological Injection Limits and Consequences for Carbon Management Costs," 30th USAEE/IAEE North American Conference, SAND2011-5975C, Washington, D.C., October 9 – 12, 2011.
  - Kobos, P.H., Roach, J.D., Klise, G.T., Krumhansl, J.L., Heath, J.E., Dewers, T.A., Borns, D.J., McNemar, A. and M.A. Cappelle, "Expanding the Potential for Saline Formations: Modeling Carbon Dioxide Storage, Water Extraction and Treatment for Power Plant Cooling," 10th Annual Conference on Carbon Capture and Sequestration, DOE/NETL, SAND2011-2713C, Pittsburgh, PA, May 2 − 5, 2011.
  - Kobos, P.H., Roach, J.D., Klise, G.T., Krumhansl, J.L., Dewers, T.A., Heath, J.E., Dwyer, B, Borns, D.J., McNemar, A., "Storing Carbon Dioxide in Saline Formations: Analyzing Extracted Water Treatment and Use for Power Plant Cooling" 29th USAEE/IAEE North American Conference, SAND2010-5972C, Calgary, Canada, October 14 – 16, 2010.
  - Kobos, P.H., Roach, J.D., Klise, G.T., Krumhansl, J.L., Dewers, T.A., Dwyer, B.P., Heath, J.E., Borns, D.J. and A. McNemar, "Saline Formations, Carbon Dioxide Storage, and Extracted Water Treatment: A National Assessment Tool," 9th Annual Conference on Carbon Capture and Sequestration, DOE/NETL, SAND2010-2647C, Pittsburgh, PA, May 10 − 13, 2010.
  - Kobos, P.H., Krumhansl, J.L., Dewers, T.A., Heath, J.E., Cappelle, M.A., Borns, D.J., Klise, G.T., Dwyer, B.P. and A. McNemar, "Combining Power Plant Water Needs and Carbon Storage using Saline Formation: An Assessment Tool." 8th Annual Conference on Carbon Capture and Sequestration, DOE/NETL, SAND2009-2557C, Pittsburgh, PA, May 4 − 7, 2009.
  - Kobos, P.H., Cappelle, M.A., Krumhansl, J.L., Dewers, T., Borns, D.J., Brady, P.V. and A. McNemar, "Using Saline Aquifers for Combined Power Plant Water Needs and Carbon Sequestration," 28th Annual USAEE/IAEE N. American Conference, SAND2008-6482C, New Orleans, LA, December 3 − 5, 2008.

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High Efficiency Water Management Strategies for Power Plant Operation

S. Altman (SNL) & I. Aurelio (NETL)

Three Tasks

- **Cooling tower side-stream treatment**
- **Controlling silica scaling**
- **Power plant waste heat for water treatment**

Desalination 285 (2012) 177–183

Contents lists available at SciVerse ScienceDirect

ELSEVIER

Desalination

journal homepage: www.elsevier.com/locate/desal

Membrane treatment of side-stream cooling tower water for reduction of water usage

Susan J. Altman [a,*], Richard P. Jensen [b], Malynda A. Cappelle [c], Andres L. Sanchez [d], Randy L. Everett [a], Howard L. Anderson Jr. [a], Lucas K. McGrath [e]

Produced

- 1 Peer-Reviewed Publication
- 4 SANDIA Reports

Demonstrated water savings with membrane treatment of cooling tower water

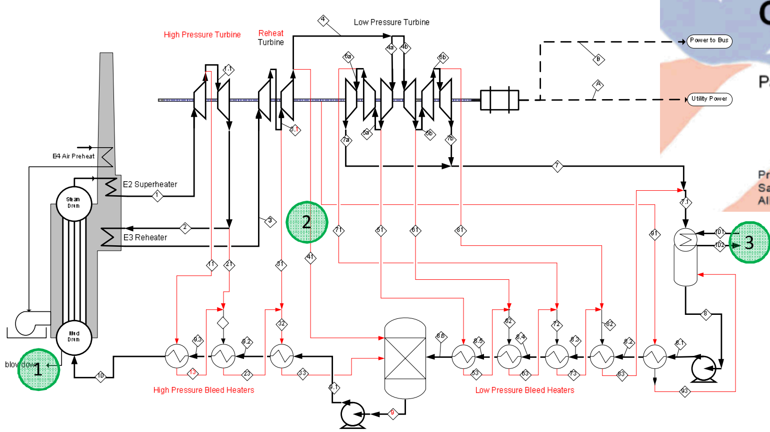
SANDIA REPORT
SAND2011-2859
Unlimited Release
Printed June 2011

Flue Gas Injection Control of Silica in Cooling Towers

Patrick V. Brady, Susan J. Altman, and Howard L. Anderson, Jr.

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Analyzed three sources for waste heat for water treatment



Developed economically feasible method to coagulate silica

Demonstrated method to keep silica in solution at higher concentrations and for a longer time.

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WECSsim: a dynamic analysis tool

Summary | Power Plant | CO_2 Capture | Carbon Sequestration | Extracted Water | Power Costs

The National Water, Energy and Carbon Sequestration Simulation (WECSsim) Model

Model Development Authors:
P.H. Kobos, J.D. Roach, G.T. Klise
J. Heath, T. Dewers, K. Gutierrez, S. McKenna, D.J. Borns

Evaluate a single powerplant

Evaluate 2005 U.S. powerplant fleet

Version 1.0, September 2011; Working Version, as of 2/2012.

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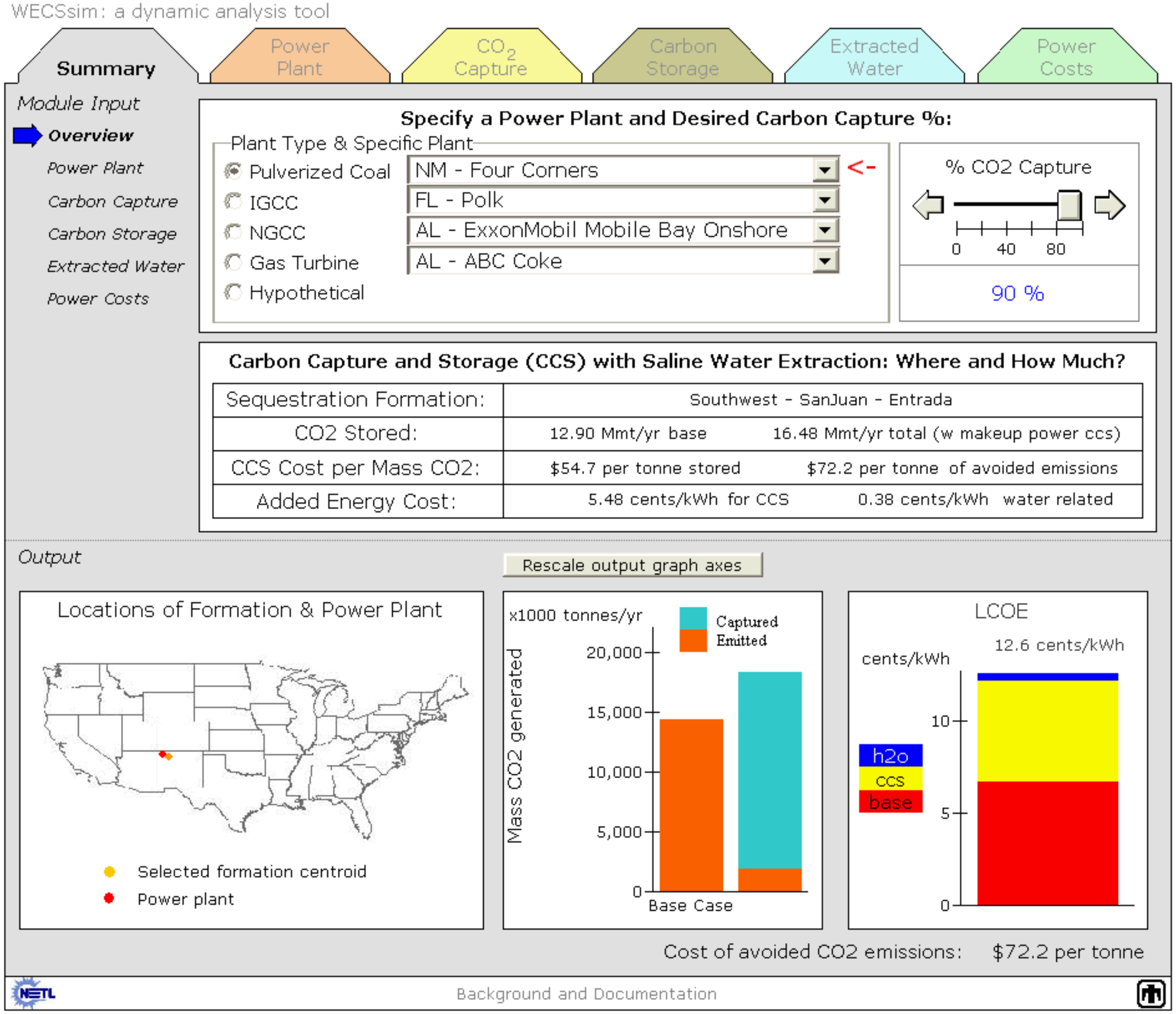

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WECSsim: a dynamic analysis tool

Summary | **Power Plant** | CO_2 Capture | Carbon Storage | Extracted Water | Power Costs

Module Input

Summary

Plant location

Plant type & size

Water use

LCOE

Specify a Power Plant (Existing or Hypothetical):

Plant Type & Specific Plant

- (•) Pulverized Coal — NM - Four Corners <-
- ( ) IGCC — FL - Polk
- ( ) NGCC — AL - ExxonMobil Mobile Bay Onshore
- ( ) Gas Turbine — AL - ABC Coke
- ( ) Hypothetical

The radio-buttons and dropdowns set the default power plant parameters to values for any eGRID 2007 plant (first four radio-button options) or an entirely user specified ("Custom") plant. In either case, resulting model defaults can be changed individually as well.

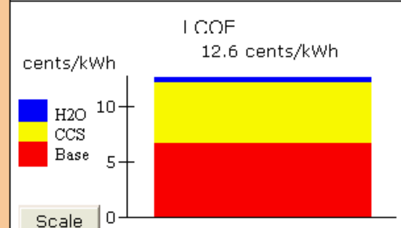
Plant type	PC-Subcritical			
Capacity & Capacity Factor	2,270 MW		0.7854	
CO2 Generation Rate	2,051 lbs/MWh			
Latitude - Longitude	Lat	36°41'24"	Long	-108°28'53"

Output

Power Plant Location

Key Information from Power Plant Module

Plant type	PC-Subcritical
Base electricity generation	15,403.9 GWh/yr
Base CO2 generation	15,797,847.7 tons/yr
Cooling type	Cooling tower
Base water withdrawals	643.1 MGD
Base water consumption	1.6 MGD



Background and Documentation

WECSsim: a dynamic analysis tool

Summary | Power Plant | CO_2 Capture | Carbon Storage | Extracted Water | Power Costs

Module Input

Summary

Parasitic Energy

Make-up Power

Direct Water Use

Carbon Capture Module Inputs Summary

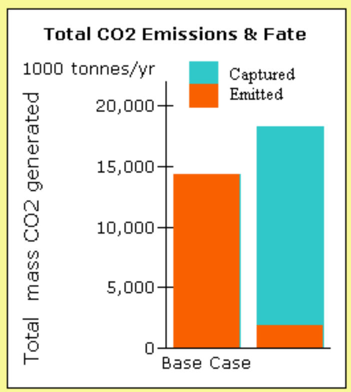
Plant Type	Pulverized coal subcritical
% Base CO2 Captured (CC)	90 %
Water withdrawal demand specific to CC & compression	298 gal/tonne CC
Make-up Power (MUP) Plant Type	PC-Subcritical
MUP CO2 Production Rate	1,900 lbs/MWh
% MUP CO2 Captured	90 %
MUP LCOE	13.1 cents/kWh
MUP Plant Cooling Type	Cooling tower
MUP water withdrawal rate	22.2 MGD

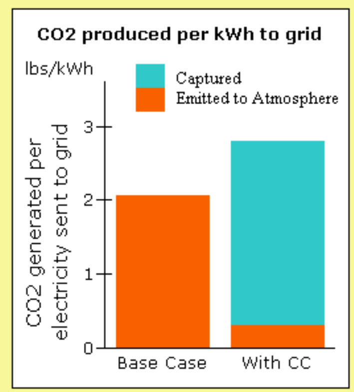
Output

Rescale output graph axes

CO2 Capture Summary Values

Base plant type	PC-Subcritical
% CO2 Captured (CC)	90 %
Parasitic Energy Loss	30 %
=	534,857 kW
Make-up plant type	PC-Subcritical
Make-up plant cooling type	Cooling tower
Added water withdrawal demand	3 %
=	22 MGD
Total CC	16.5 Mmt/yr
LCOE of CC	5.4 cents/kWh





Background and Documentation

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WECSsim: a dynamic analysis tool

Summary | Power Plant | CO_2 Capture | **Carbon Storage** | Extracted Water | Power Costs

Module Input

Summary

Sink ID & Location

Sink Area

Sink Depth & Thickness

Sink TP CO2 D

Sink Porosity

Sink Permeability

Injection Wells

Sink Storage Resource

Carbon Storage Target (NatCarb Partnership - Basin - Formation)

Southwest - SanJuan - Entrada

Formation Centroid	36°24'35" N -107°42'43" W
Formation footprint area	29,181.6 km²
Formation depth	5,887 ft
Formation thickness	420 ft
Formation average porosity	0.168
Formation geometric mean permeability	396.9 mD
Formation temperature	59°C
Formation pressure	175.8 bar

Output

Carbon Storage Target	
Southwest - SanJuan - Entrada	
Sink life for this CO2 only	550 yr
Sequestration depth	5,887 ft
Initial temp. at seq. depth	59°C
Initial pressure at seq. depth	176 bar
Resulting initial CO2 density	727 kg/m³
CO2 to be sequestered	16.5 Mmt/yr
Power Plant to sink distance	0 mi
# injection wells required	10
LCOE CO2 transport & seq.	0.05 cents/kWh

Locations of Formation & Power Plant

Selected formation centroid location (36°24'35" N -107°42'43" W)

Power plant location (set on Power Plant Tab) (36°41'24" N -108°28'53" W)

NETL Background and Documentation

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WECSsim: a dynamic analysis tool

Summary | Power Plant | CO_2 Capture | Carbon Storage | **Extracted Water** | Power Costs

Module Input

- ***Summary***
- *Quantity & Quality*
- *Extraction Wells*
- *Water Treatment*
- *Brine Disposal*

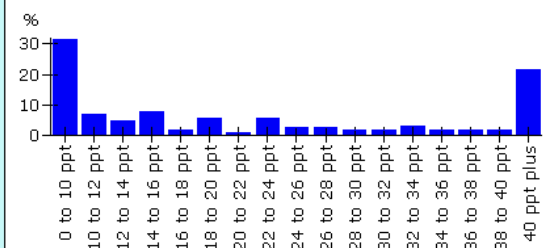
Extracted Water Module Inputs Summary

Saline formation targeted	Southwest - SanJuan - Entrada
Deep saline water extraction rate	25.25 MGD
Number of extraction wells	10
Extraction depth	2500 to 5000 ft
Minimum salinity threshold	10 ppt
Maximum salinity threshold	30 ppt
Average salinity of extracted water	19 ppt
Treated water stream	16.64 MGD
% new (CCS) H2O demands met	75 %
Brine disposal method	injection

Output

Extraction formation:	
Southwest - SanJuan - Entrada	
Holes drilled per extraction well:	2.6
Number of extraction wells:	10
Average TDS of extracted water:	19 ppt
RO treatment plant efficiency:	66 %
Brine concentrate (bc) disposal:	injection
Treated water stream:	16.6 MGD
% new (CCS) H2O demands met:	75 %
Cost of extraction and transport:	\$4.66 per 1000 gal
Cost of treatment and bc disposal:	\$5.10 per 1000 gal
Total treated water cost:	\$9.76 per 1000 gal

Distribution of water quality in target formation at depths of: 2500 to 5000 ft



Rescale

Salinity Intervals

Caution: Distribution is from potentially intersecting well records and thus only an estimate of tds in the formation

NETL | Background and Documentation

WECSsim: a dynamic analysis tool

Summary | Power Plant | CO_2 Capture | Carbon Storage | Extracted Water | **Power Costs**

Module Input

Summary

Base year & cap factors

Base LCOE

CCC Costs - Amine

CCC Costs - Selexol

CO2 Pipeline Costs

Injection Well Costs

H2O Extraction Costs

H2O Pipeline Costs

H2O Treatment Costs

Brine Disposal Costs

CCS Costs Summary Values

$ Display Year	2010
Power Plant Capitilization Factor	8.02 %/yr
Saline Formation Capitilization Factor	8.02 %/yr
Base LCOE at Plant	6.71 cents/kWh
Make-up Power LCOE	13.1 cents/kWh
CCC Costs Amine Scrubbing	1.5 cents/kWh
CCC Costs Selexol (IGCC)	? cent/kWh
CO2 Pipeline Costs	0 cents/kWh
CO2 Injection Well Costs	0.05 cents/kWh
H2O Extraction Well Costs	0.18 cents/kWh
H2O Pipeline Costs	0 cents/kWh
H20 Treatment Costs	0.19 cents/kWh
Brine Disposal Costs	0.01 cents/kWh

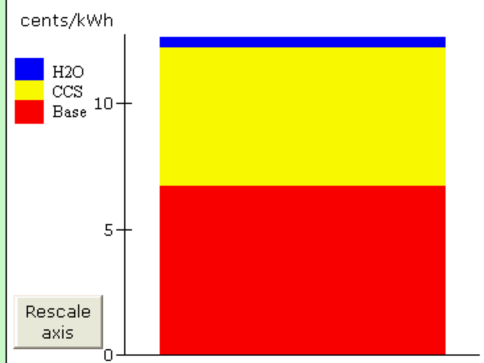
Output

Power Cost Results
In 2010 dollars

$/mass CO2 stored
$/reduced CO2 emissions

Marginal LCOE for treated water:	0.38 cents/kWh
Cost of treated water:	$3.55 per tonne
Marginal LCOE for CO2 transport:	0 cents/kWh
Length of CO2 pipeline:	0 mi
Cost of CO2 transport:	$0 per tonne
Marginal LCOE for CO2 injection:	0.05 cents/kWh
Cost of CO2 injection:	$0.45 per tonne
Marginal LCOE for Make-Up Power:	3.93 cents/kWh
Marginal LCOE for CCC:	1.5 cents/kWh
CCC Cost Including Make-Up Power:	$50.72 per tonne
Base LCOE:	6.71 cents/kWh

Total LCOE with CCS 12.57 cents/kWh



Background and Documentation

Sandia National Laboratories