

# Tenth Annual Conference on Carbon Capture & Sequestration

SAND2011-2756C

## *Ancillary Benefits of CCS Systems*

### **Expanding the Potential for Saline Formations: Modeling Carbon Dioxide Storage, Water Extraction and Treatment for Power Plant Cooling**

Peter H. Kobos, Jesse D. Roach, Geoff T. Klise, Jim L. Krumhansl,  
Jason E. Heath, Thomas A. Dewers, David J. Borns,  
Andrea McNemar, and Malynda A. Cappelle

May 2-5, 2011 • David L. Lawrence Convention Center • Pittsburgh, Pennsylvania

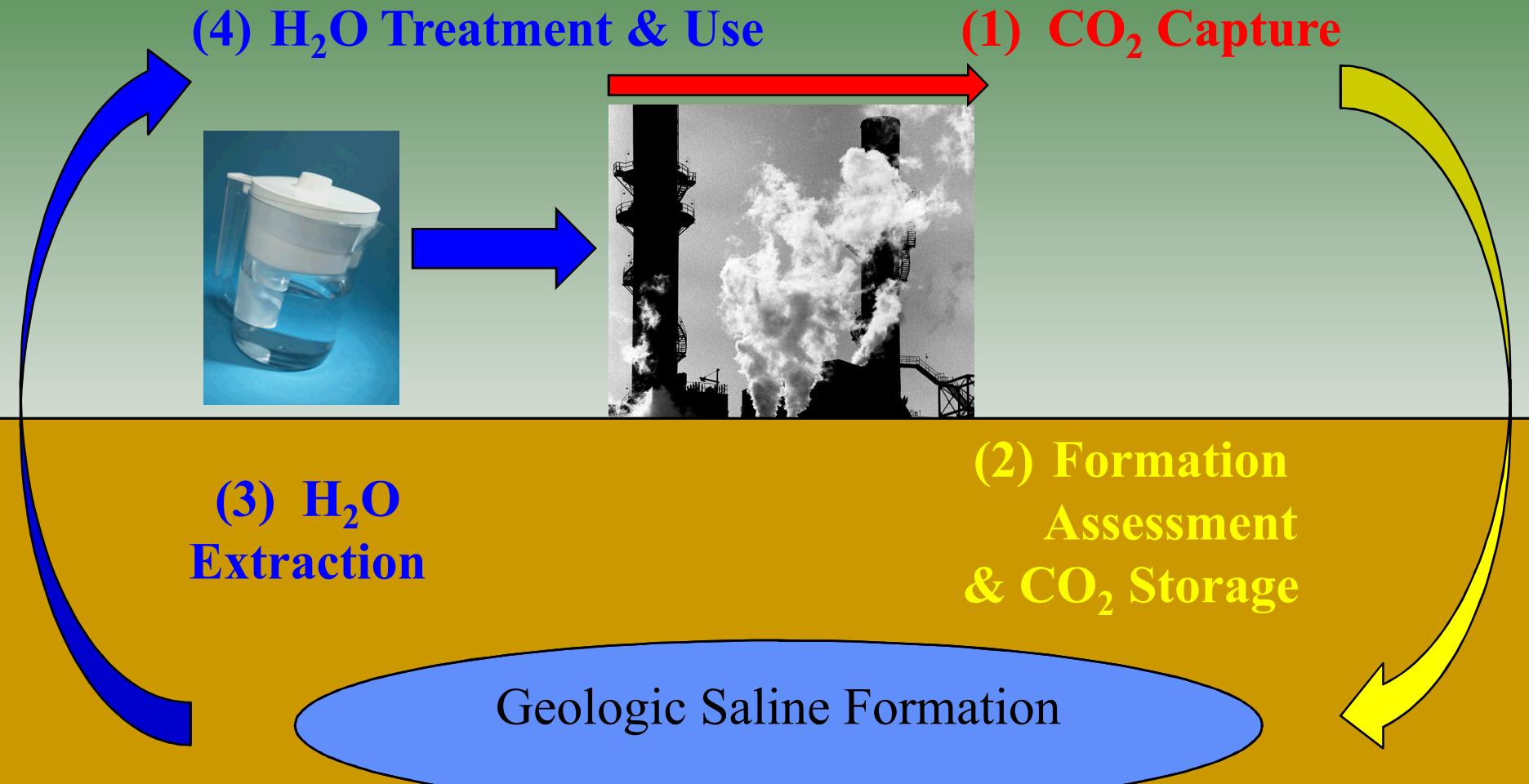
Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Working Results.



Tenth Annual Conference on Carbon Capture & Sequestration



# The Water, Energy and CO<sub>2</sub> Storage (WECS) Model: *Addressing Uncertainty in the Data*



Timeline

# Project Timeline & Goals

2008

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

2009

- Completed Phase II:
  - Additional Geosystems Analysis
    - Detailed TOUGH 2 modeling

2010

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

2011

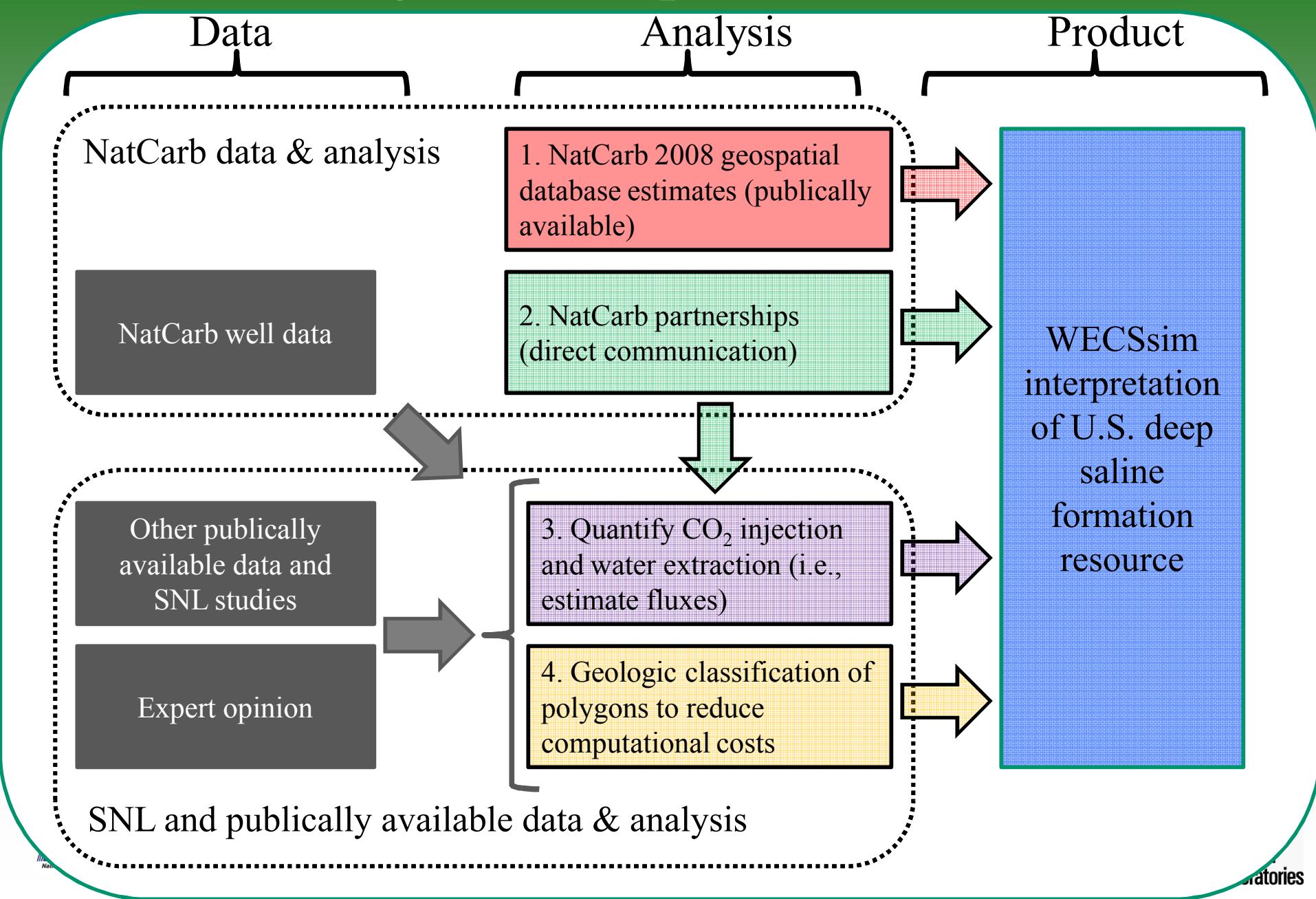
- Phase IV & V:
  - Expanding the role of uncertainty within the model

2012

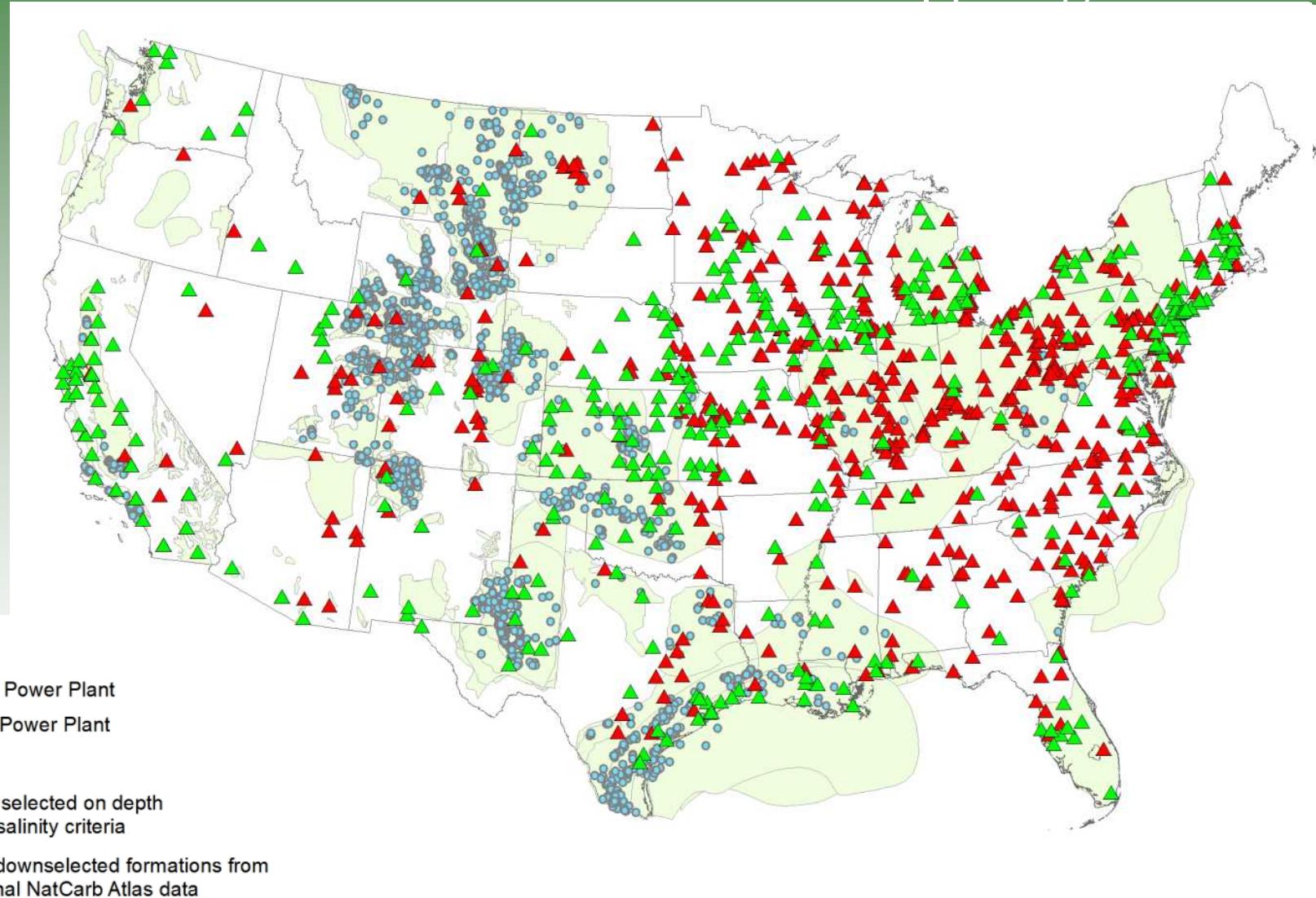


	Single Source (power plant)	Multiple Sources
Single Sink (saline formation)	WECS	
Multiple Sinks	WECSsim	

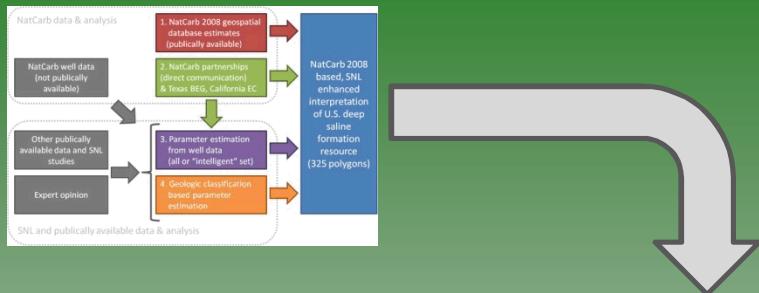
# Assessing U.S. deep saline formations



# Geological CO<sub>2</sub> Storage Database is Incomplete: *Makes Source/Sink Matching Difficult*



# Limited Saline Formation Data



Data availability by source for 325 polygons derived from NatCarb 2008

Data Source	CO <sub>2</sub> storage capacity	Area	Depth	Thickness	Porosity	TDS	Temp	Pressure
NatCarb 2008	42%	100%	0%	0%	0%	0%	0%	0%
Partnerships	42%	100%	62%	64%	55%	18%	44%	45%
Well records	NA	NA	70% <sup>1</sup>	70% <sup>1</sup>	0%	70% <sup>1</sup>	100% <sup>2</sup>	NA
Geologic class	NA	NA	NA	NA	? % <sup>3</sup>	0%	NA	NA
<b>No estimate</b>	<b>16%</b> (52)	<b>0%</b> (0)	<b>14%<sup>4</sup></b> (47)	<b>14%<sup>4</sup></b> (47)	<b>0 - 45%</b> (0 - 147)	<b>14%<sup>4</sup></b> (47)	<b>14%<sup>4</sup></b> (47)	<b>14%<sup>4</sup></b> (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. Current attempts to classify all 325 polygons according to geology may not result in reliable data estimates for all polygons.
4. 14% of polygons (47 of 325) have no depth, thickness, or salinity information and no potentially intersecting wells.

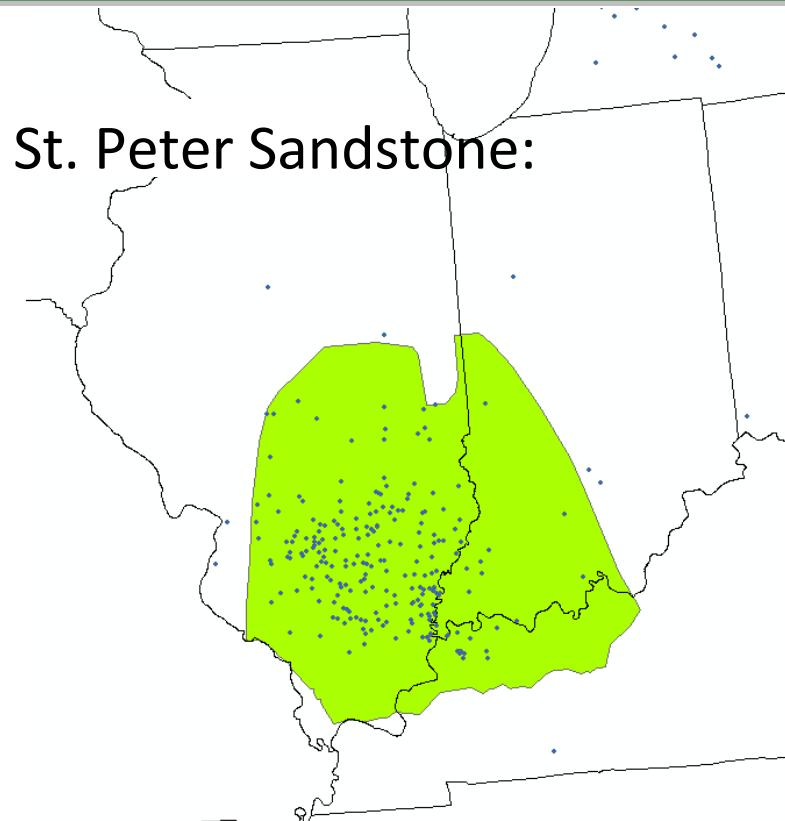
# Example formations: The good



St. Peter Sandstone:

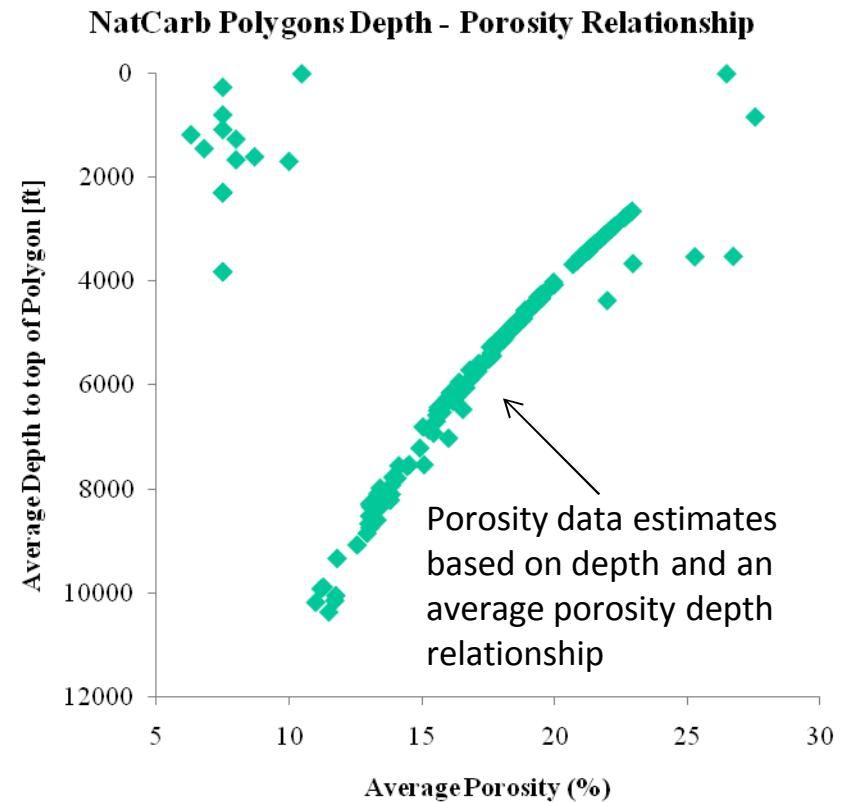
Includes NatCarb or MGSC derived estimates and ranges for capacity, depth, thickness, porosity, pressure, temperature, and salinity, as well as 892 potentially intersecting wells.

# Example formations: The good, but...



Includes NatCarb or MGSC derived estimates and ranges for capacity, depth, thickness, porosity, pressure, temperature, and salinity, as well as 892 potentially intersecting wells.

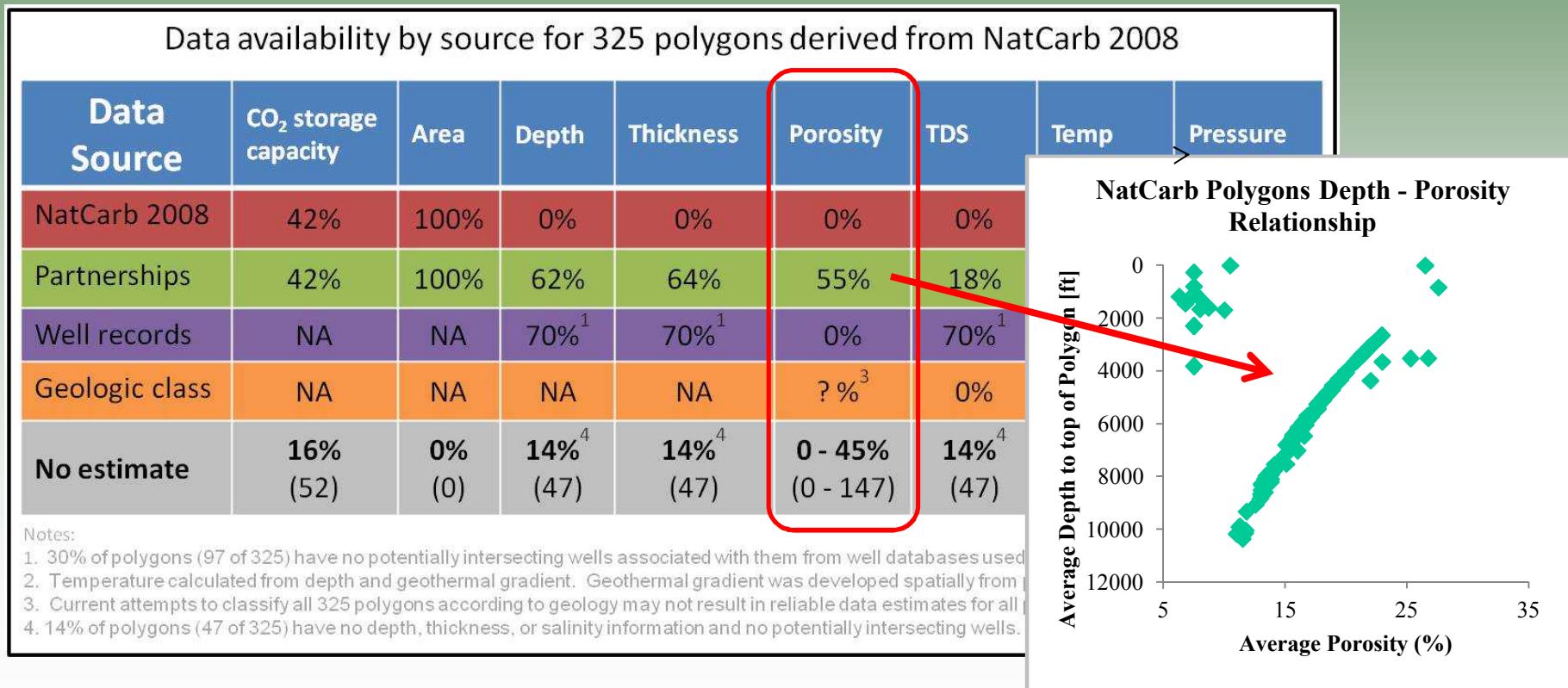
But caution with reported data is advisable:



Of the 156 polygons w/NatCarb or partnership depth and porosity info., but limited actual porosity data...

# Porosity & Permeability

- From data analysis, recall that porosity data is limited
- Additionally, permeability/injectivity data is needed for economic analysis



# Uncertainty and the Well Injectivity Index

**$I$**  well injectivity index;  
measure of the “ease”

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

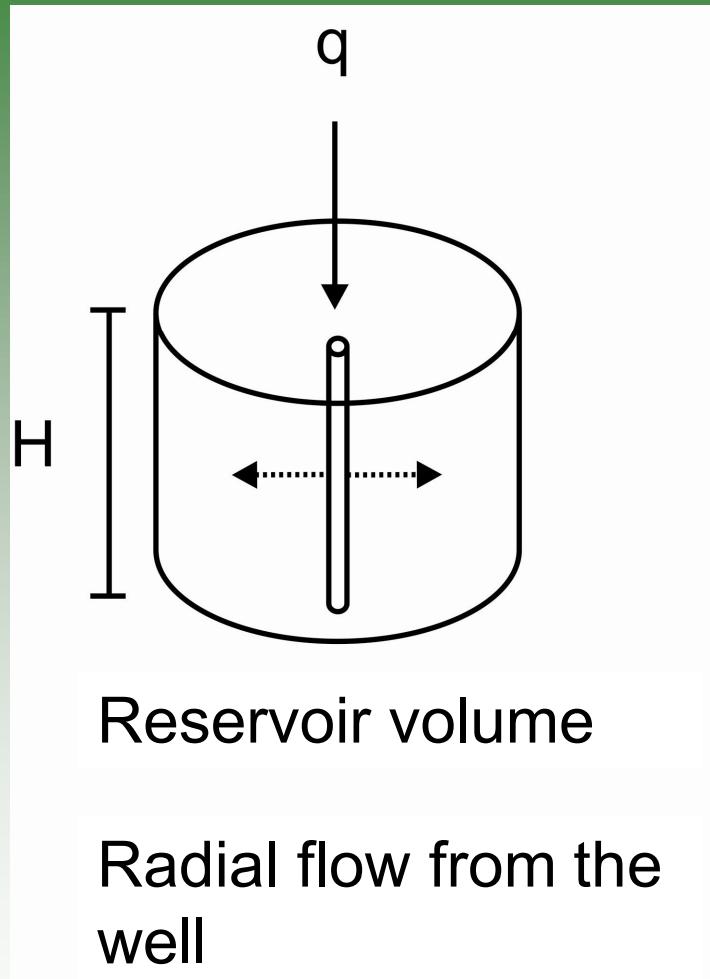
of injecting CO<sub>2</sub> into  
the well

**$q$**  volumetric flow rate

**$\Delta P$**  the pressure gradient

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

(Bryant and Lake, 2005)

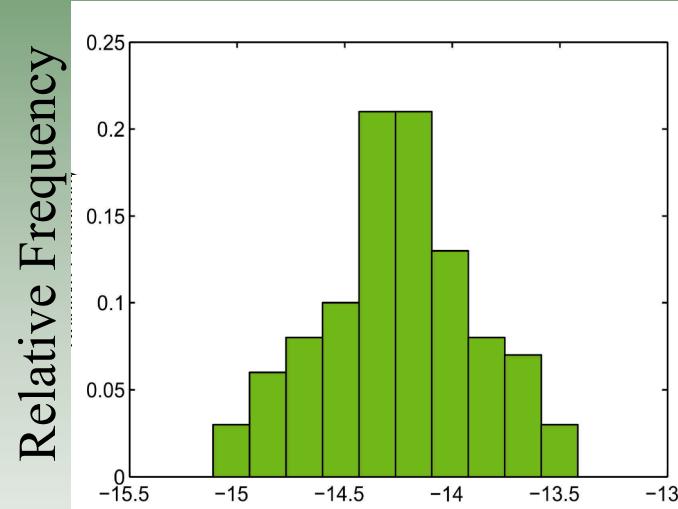
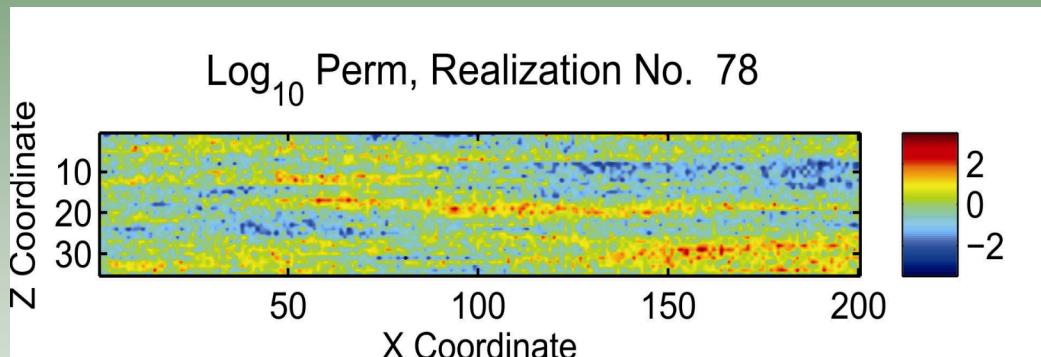


# Generating pdfs of Well Injectivity Index

Use geostatistics to generate multiple realizations of relevant parameter fields



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



Log<sub>10</sub>(averaged permeability)

Feed the “properly” averaged parameters into equation to get a pdf of  $I$

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

# CO<sub>2</sub> Storage Module Inputs - 1

## User Specified Saline Formation Info.:

- Formation utilized



WECSSim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Selected Sequestration Formation		
Partnership	Basin Name	Formation Name
<input checked="" type="radio"/> Model Default	SECARB	Tuscaloosa Group
<input type="radio"/> Custom: (changeable with dropdown)	New (not in database)	
	Not in database	Not in database
	Not in database	Not in database

Locations of Formation & Power Plant



Selected formation centroid location  
Power plant location (set on Power Plant Tab)

Formation Location (centroid lat long, area, average surface elevation)		
Latitude	Longitude	Surface Elevation
<input checked="" type="radio"/> Default	*****	-89°53'55" 203 ft
<input type="radio"/> Custom (changeable)	36°	-108° 6,562 ft

Power plant to formation distance

<input checked="" type="radio"/> Default	0 mi
<input type="radio"/> Custom (changeable)	0 mi

Formation Shape and Areal Extent

Approximate formation extent from centroid in 8 directions

Default		
W	N	NE
139 mi	199 mi	87 mi
81 mi	Centroid	107 mi
78 mi	201 mi	143 mi

Custom (changeable)		
W	N	NE
14 mi	13 mi	12 mi
15 mi	Centroid	11 mi
16 mi	17 mi	18 mi

Maximum distance power plant to default formation

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



50 mi

Formation Footprint Area

Default is based on geometry specified to the left.

<input checked="" type="radio"/> Default	46,521 mi <sup>2</sup>
<input type="radio"/> NatCarb	56,326 mi <sup>2</sup>
<input type="radio"/> Custom (changeable)	1,000 mi <sup>2</sup>

Sequestration Depth (below land surface)

Choose from "Reported" values from partnership data and reports, "SNL wells" values from Sandia National Labs formation specific well analysis, "PI wells" values from analysis of all potentially intersecting wells, or enter a user specified "Custom" value.

<input checked="" type="radio"/> Default	3,652 ft
Default source:	Texas BEG
<input type="radio"/> Reported	3,652 ft
<input type="radio"/> SNL wells	7,778 ft
<input type="radio"/> PI wells	3,500 ft
<input type="radio"/> Custom (changeable)	5,000 ft

Formation Thickness

Choose from "Reported" values from partnership data and reports, "SNL wells" values from Sandia National Labs formation specific well analysis, "PI wells" values from analysis of all potentially intersecting wells, or enter a user specified "Custom" value.

<input checked="" type="radio"/> Default	153 ft
Default source:	Texas BEG
<input type="radio"/> Reported	153 ft
<input type="radio"/> SNL wells	27 ft
<input type="radio"/> PI wells	45 ft
<input type="radio"/> Custom (changeable)	500 ft

Model Inputs  
may be  
Customized

- Location related



- Shape and area



- Sequestration depth  
& formation thickness

Input

# CO<sub>2</sub> Storage Module Inputs - 1

## User Specified Saline Formation Info.:

- Formation utilized
- Location related
- Shape and area
- Sequestration depth & formation thickness

WECsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Formation Utilized

Model Default: SECARB  
Custom: (changeable with dropdown)  
New (not in database)  
Not in database

Locations of Formation & Power Plants

Selected for formation centroid location  
Power plant location (set on map)

Formation Shape

Approximate formation extent

Default: (changeable)  
Default shape from simplification of NatCap 2d shape.  
Custom: (changeable)

Formation Thickness

Sequestration Depth (below land surface)

Choose from "Reported" values from partnership data and reports, "SNL wells" values from Sandia National Labs formation specific well analysis, "PI wells" values from analysis of all potentially intersecting wells, or enter a user specified "Custom" value.

	3,652 ft
Default Default source: Texas BEG	3,652 ft
Reported	3,652 ft
SNL wells	7,778 ft
PI wells	3,500 ft
Custom (changeable)	5,000 ft

Formation Thickness

Choose from "Reported" values from partnership data and reports, "SNL wells" values from Sandia National Labs formation specific well analysis, "PI wells" values from analysis of all potentially intersecting wells, or enter a user specified "Custom" value.

	153 ft
Default Default source: Texas BEG	153 ft
Reported	153 ft
SNL wells	27 ft
PI wells	45 ft
Custom (changeable)	500 ft

# CO<sub>2</sub> Storage Module Inputs - 2

# Including Uncertainty:

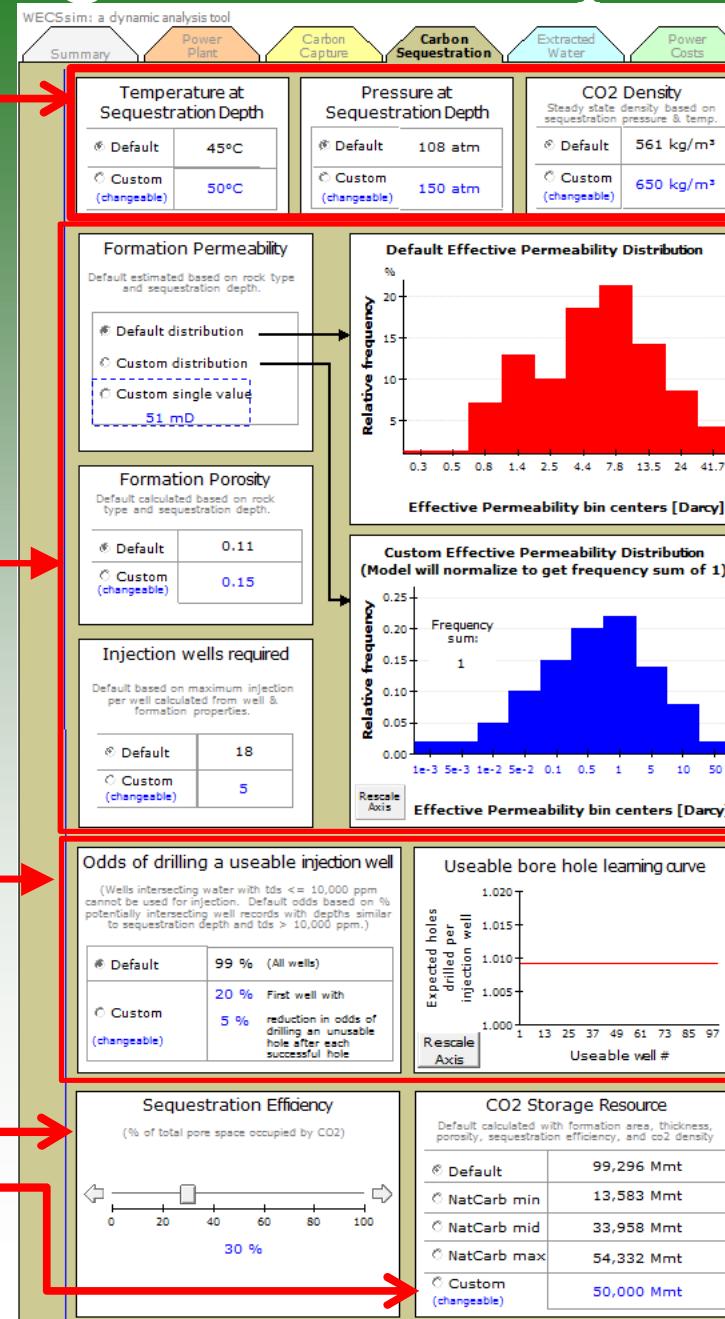
- Temperature, pressure,  $\text{CO}_2$  density —

- Permeability, porosity,  
# of injection wells —

- Odds of drilling a useable injection well (water quality related)

- Sweep efficiency

- Total storage resource



# Power Plant Module Inputs

## User Specified Power Plant Info.:

- Type
- Location
- Size
- CO<sub>2</sub> production
- Water use
- LCOE

WECSsim: a dynamic analysis tool

**Power Plant Specs:**

<b>Power Plant Type</b>	<b>Power Plant Location</b>
<input checked="" type="radio"/> Pulverized coal subcritical <input type="radio"/> Pulverized coal supercritical <input type="radio"/> Integrated gasification combined cycle <input type="radio"/> Natural gas turbine <input type="radio"/> Natural gas combined cycle	 Latitude: 30°   Longitude: -94°   Elevation: 4 m <small>(click #s to change)</small>

<b>Installed Capacity</b>	<b>Capacity Factor</b>
0 <input type="text" value="1,848"/> MW   4,000	0.0 <input type="text" value="0.72"/> 1.0

<b>CO<sub>2</sub> Production Rate</b>	<b>Expected Year Online and Offline</b>
<input checked="" type="radio"/> Use default: 1,900 lbs/MWh <input type="radio"/> Use custom: 2,200 lbs/MWh <small>(click # to change)</small>	Start Yr: NA   End Yr: 2040 <input checked="" type="radio"/> Existing plant <input type="radio"/> New plant build <small>(click #s to change)</small>

<b>Cooling Technology</b>	<b>Base Water Use Rates</b>
<input type="radio"/> Once through <input checked="" type="radio"/> Cooling tower(s) <input type="radio"/> Cooling pond(s) <input type="radio"/> Dry cooling	Withdrawal   Consumption <input checked="" type="radio"/> Use default: 670 gal/MWh   520 gal/MWh <input type="radio"/> Use custom: 670 gal/MWh   520 gal/MWh <small>Defaults based on Tables D-1 and D-4 of NREL 400/2008/1339 and Figure 4-2 and B-1 of NREL 402/2008/08018</small>

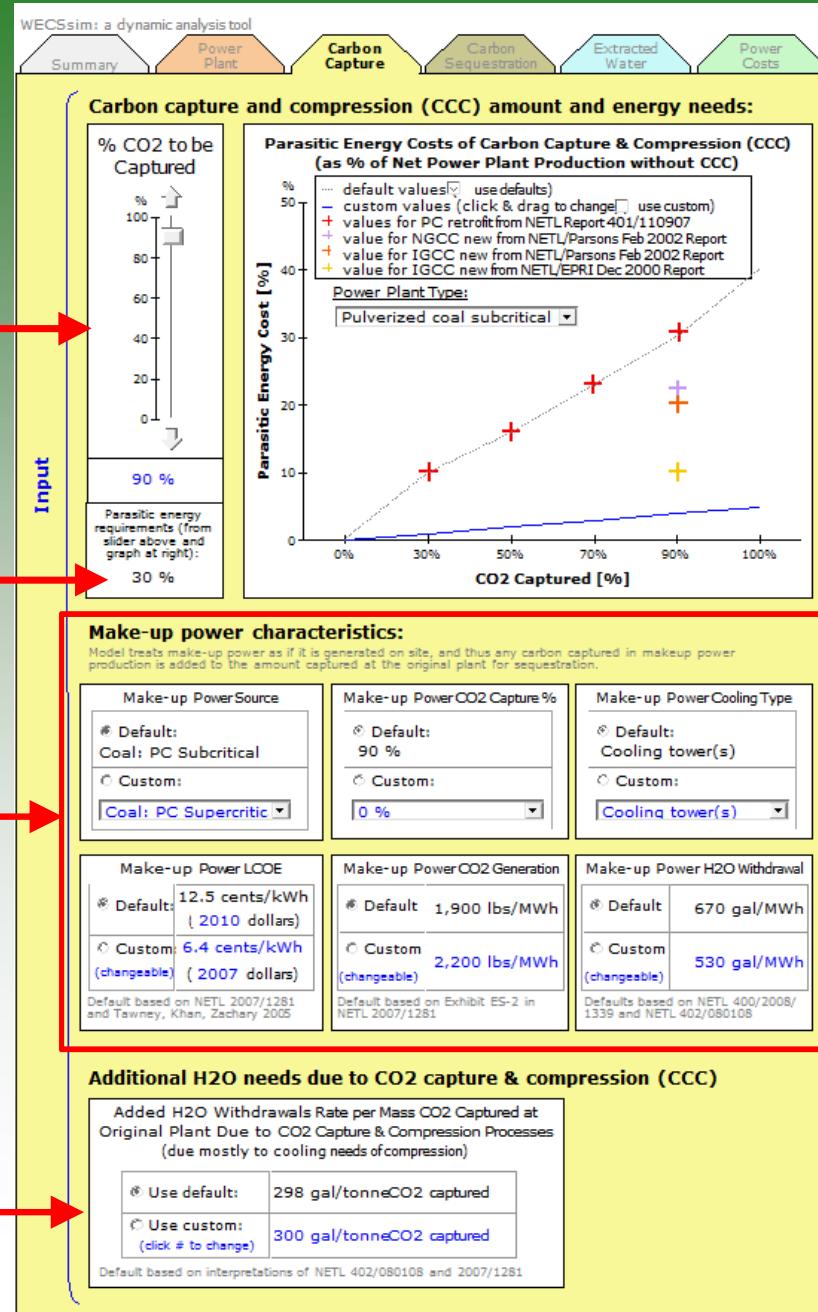
<b>Base Levelized Cost of Electricity (LCOE)</b>				
Total	Fuel Costs	Cooling	All Other	\$ Year:
<input checked="" type="radio"/> Default: 6.7 cents/kWh <input type="radio"/> Custom: (changeable) 6.4 cents/kWh	= 2.1 cents/kWh + 0.3 cents/kWh + 4.4 cents/kWh	+ 0.2 cents/kWh	+ 4.2 cents/kWh	2010 2007

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

# CO<sub>2</sub> Capture Module Inputs

## User Specified Carbon Capture Information:

- % to be captured
- Energy required
- Make-up power characteristics
- Additional H<sub>2</sub>O use



# Extracted H<sub>2</sub>O Module

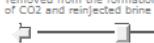
## User Specified Water Treatment Info.:

- TDS range & extraction amount
- Probability, drilling a useable extraction well
- Extraction depth
- Expected extracted TDS
- Brine disposal related
- Number of extraction wells required

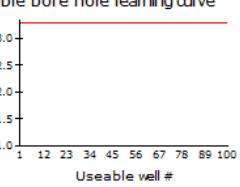
WECSSim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Inputs independent of power plant or sequestration formation selected:

Min useable TDS (potential drinking supply below this)	Max useable TDS (highest salinity treated in model)	H2O net volume extraction as % of CO2 volume injection (100% means the same volume of water is removed from the formation as the volume of CO2 and re injected brine (if any) added)
 0 10 20 30 10 ppt	 0 50 100 30 ppt	 0 50 100 150 200 100% = 5.45 MGD

Inputs dependent on sequestration formation selected:  
(Formation selected \$RCARR Gulf Coast Oligocene )  
Default question marks (?) mean that there is not well data to support an estimate, so a custom input is required.

Probability of drilling a useable well (default based on useable tds range, & tds distribution in formation)	Useable bore hole learning curve
<input checked="" type="radio"/> Default 30 % (All wells)	 Expected holes drilled per extraction well Rescale Axis
<input type="radio"/> Custom (changeable) 20 % First well with 5 % reduction in odds of drilling an unusable hole after each successful hole	 Useable well #

Extraction wells depth (default based on minimizing drilling costs resulting from probability of drilling a useable well)	Average salinity from useable wells (average salinity of well records with acceptable TDS potentially intersecting selected formation)
<input checked="" type="radio"/> Default 2500' to 5000'	<input checked="" type="radio"/> Default 22 ppt
<input type="radio"/> Custom (changeable) 4,725 ft	<input type="radio"/> Custom (changeable) 20 ppt

Inputs dependent on power plant:

Net evaporation rate at power plant Higher net evap means more effective evaporation ponds for brine disposal. They won't work at all unless net evap is greater than 0.	Required evaporation pond area Pond area required if brine is to be disposed of using evap ponds. ? means evap ponds won't work.
<input checked="" type="radio"/> Default -13 in/yr	<input checked="" type="radio"/> Default ? acre
<input type="radio"/> Custom (changeable) 10 in/yr	<input type="radio"/> Custom (changeable) 10 acres

Distance to free brine disposal point Distance waste brine would need to be transported for free disposal. (Default is distance to coast.)	Elevation of free brine disposal point Sea level by default
<input checked="" type="radio"/> Default 66 mi	 0 50 100 0 ft
<input type="radio"/> Custom (changeable) 0 mi	

Inputs dependent on power plant and sequestration formation selected:

Number of operating extraction wells Default based on formation thickness, porosity, and permeability.	Distance to brine injection point Distance waste brine would need to be transported for disposal by injection. Default is distance from plant to sequestration formation.
<input checked="" type="radio"/> Default 13	<input checked="" type="radio"/> Default 0 mi
<input type="radio"/> Custom (changeable) 4	<input type="radio"/> Custom (changeable) 0 mi

Selected Brine Disposal Method Unlike other custom inputs, custom option here will not alter the model selected default formation.	
<input checked="" type="radio"/> Default Transport and dump	<input type="radio"/> Custom Evaporation ponds

# Power Costs Module Inputs - 3

## User Specified Cost Info.:

- Display year for \$ amounts
- Capitalization factors
- Base LCOE (same as before)
- CO<sub>2</sub> capture, compression, & MUP costs
- CO<sub>2</sub> transport and injection costs
- Water extraction and transport costs
- Water treatment costs
- Brine disposal costs

WECSim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

**Water treatment cost parameters**

High Eff. Reverse Osmosis plant capital costs per feed flow	\$3,535,545 per MGD
Receiving, transfer, dist piping capital costs per feed flow	\$779,931 per MGD
Dollar year for capital costs listed above	2004
Annual labor costs coefficient per treatment plant capacity	171,778 (USD/yr)/(MGD)
Annual labor costs plant capacity exponential	0.2322
Dollar year for labor costs listed above	2000
High Efficiency Reverse Osmosis (HERO) base electricity use	2.41 kWh/1000gal
HERO water quality dependent marginal electricity use	0.6 kWh/1000gal/ppt
HERO membrane replacement costs ( 2000 \$)	8 cents/1000gal
HERO chemical replacement costs ( 2004 \$)	59 cents/1000gal
HERO other O&M as a function of capital costs	1.5 %/yr

Capital costs and chemical replacement costs from Zammit and DiIillo 2004 estimates of costs for a HERO plant with 1316 gpm model feed flow. "Use of Produced Water in Recirculating Cooling Systems at Power Generating Facilities" Deliverable #3  
Labor costs from best fit exponential equation based on data in Figure 9-37 of "Desalting Handbook for Planners" 3rd Edition, July 2003, US Bureau of Reclamation (USBR) Desalination and Water Purification Research & Development Program Report No. 72, <http://www.usbr.gov/pmts/water/media/pdfs/report072.pdf>  
Best fit equation: cost = \$171778\*PlantCapacity^0.2322  
HERO electricity use parameters based on data in Figure 7-8 of the same USBR report.  
Membrane replacement costs also based on data in the same USBR report.  
Other O&M costs as a function of capital costs is a model assumption.

**Brine disposal cost parameters**

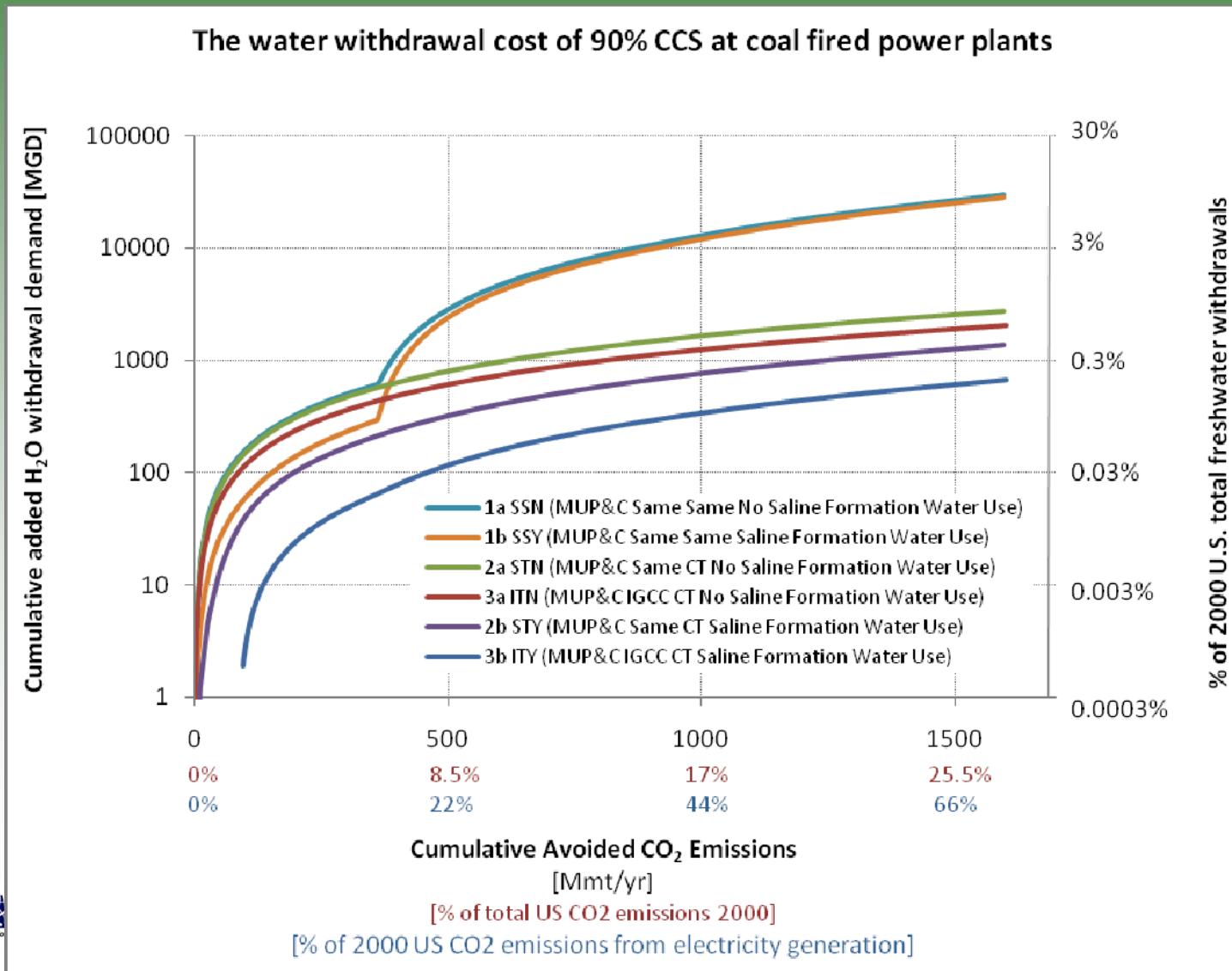
Evaporation ponds fixed capital cost:	\$19,600
Evaporation ponds variable capital cost:	\$244,900 per acre
Evaporation ponds O&M as % of capital cost:	1.5 %/yr
Injection wells fixed capital cost:	\$2,359,271
Injection wells variable capital cost:	\$194,893 per MGD
Injection pipelines and wells O&M as % of capital cost:	1.5 %/yr
Dollar year for evaporation ponds and injection well costs:	2000

All brine pipeline cost parameters are the same as for the water supply pipeline

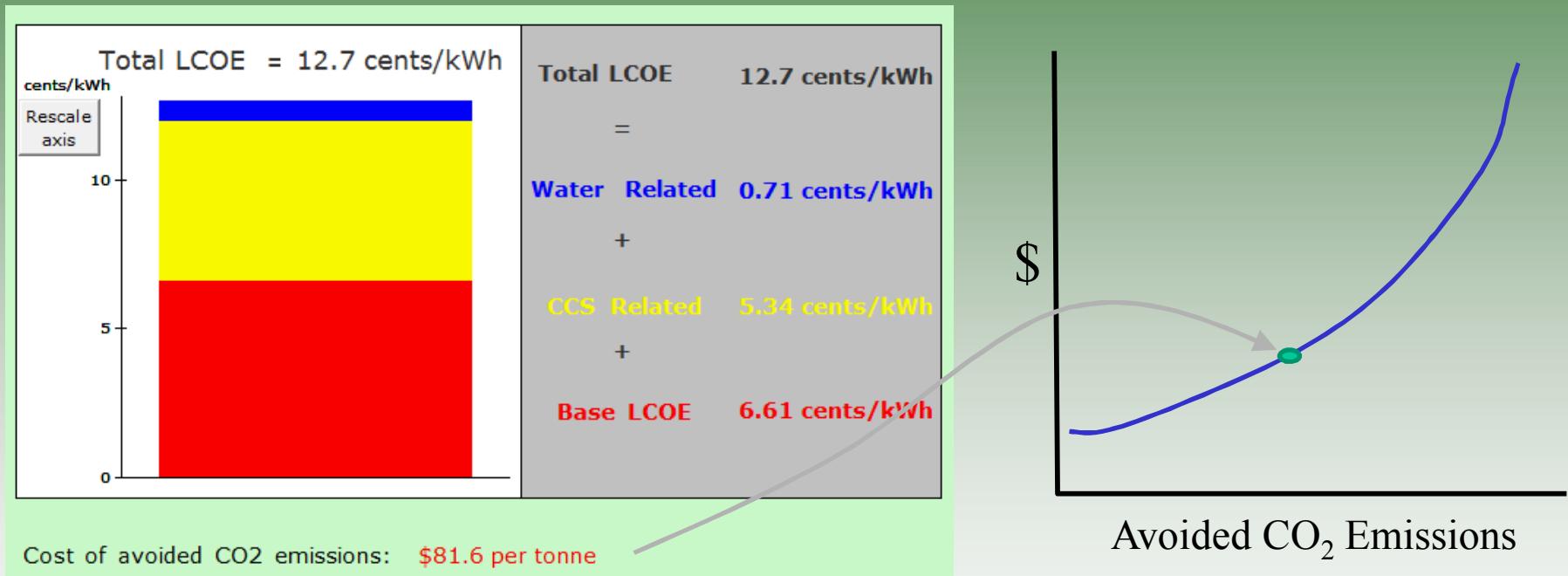
Evaporation ponds capital costs from best fit equation to data in Figure 9-12 of "Desalting Handbook for Planners" 3rd Edition, July 2003, US Bureau of Reclamation (USBR) Desalination and Water Purification Research & Development Program Report No. 72, <http://www.usbr.gov/pmts/water/media/pdfs/report072.pdf>  
Injection wells capital costs from best fit equation to data in Figure 9-13 of the same.  
Other O&M costs as a function of capital costs is a model assumption.

# WECSsim Results:

*Represents 6 Least Water Intensive paths to reduced CO<sub>2</sub> emissions for given technology*



# WECSSim Results: *Similar Full Economic Analysis Underway*



Note: Illustrative Example at this time

# Conclusions

- **Refining the National WECSSim Model**
  - Coupled CCS and Water Extraction/Treatment for Power Plant Cooling
- **Uncertainty in the Saline Formation Data**
  - Limits the possible Analysis
- **Using a national-level systems approach**
  - Illustrate the distribution of the CO<sub>2</sub> storage resource and magnitude of costs associated with CCS

# Tenth Annual Conference on Carbon Capture & Sequestration

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**Thank You.**

Peter H. Kobos, Jesse D. Roach, Geoff T. Klise, Jim L. Krumhansl,  
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# Backup Slide: Power Costs Module Inputs

## User Specified Cost Information:

- 1

- Display year for \$ amounts
- Capitalization factors
- Base LCOE (same as before)
- CO<sub>2</sub> capture, compression, and MUP costs
- CO<sub>2</sub> transport and injection costs
- Water extraction and transport costs
- Water treatment costs
- Brine disposal costs

WECSSim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Display year for output \$ values

1950 1960 1970 1980 1990 2000 2010 2010

Power Plant Capitalization Factor

Interest rate and loan period for default rate

Default: 8 %/yr 5 %/yr  
Custom (changeable): 17.5 %/yr 20 yr

Smaller of loan period & power plant remaining life used to calculate default capitalization factor

Base Levelized Cost of Electricity (LCOE)

Total	Fuel Costs	Cooling	All Other	\$ Year:
6.7 cents/kWh	2.1 cents/kWh	0.3 cents/kWh	4.4 cents/kWh	2010
6.4 cents/kWh	2 cents/kWh	0.2 cents/kWh	4.2 cents/kWh	2007

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, Vol. 127

CO<sub>2</sub> Capture, Compression, and Makeup Power Cost Parameters:

Cost Parameters for Amine Scrubbing Capture and Compression:

Capital costs. Fixed portion. ( 2006 \$)	\$119,453,000
Capital costs. Variable portion. ( 2006 \$)	\$112.8 yr/tonne
Variable O&M costs. Fixed portion. ( 2006 \$)	\$1,838,600 per yr
Variable O&M costs. Variable portion. ( 2006 \$)	\$6.2 per tonne
Fixed O&M costs. Fixed portion. ( 2006 \$)	\$1,556,900 per yr
Fixed O&M costs. Variable portion. ( 2006 \$)	\$4e-1 per tonne

Defaults based on data published in Table ES-1 of DOE/NETL report # 401/110907, "Carbon Dioxide Capture from Existing Coal-Fired Power Plants". Regressions created for capital cost, fixed O&M, and variable O&M costs (not including make-up power which is handled separately) as a function of carbon dioxide captured:

Cost Type	Equation	R2
Capital	CCost[Thousands of 2006\$] = 839.59*CO2Captured[tonne/hr] + 119453	0.977
Variable O&M	VOM[Thousands of 2006\$/yr] = 46.183*CO2Captured[tonne/hr] + 1828.6	0.996
Fixed O&M	FO&M[Thousands of 2006\$/yr] = 2.6896*CO2Captured[tonne/hr] + 1556.9	1

Cost Parameters for Selexol Capture and Compression (for IGCC):

Capital costs per CO <sub>2</sub> captured. ( 2006 \$)	\$190 hr/lb
Selexol fixed O&M costs per CO <sub>2</sub> captured. ( 2006 \$)	\$0.35 per tonne
Selexol variable O&M costs per CO <sub>2</sub> captured. ( 2006 \$)	\$0.57 per tonne
Additional coal use at IGCC per CO <sub>2</sub> captured. ( 2006 \$)	0.07 tons/yr/(lb/hr)
Assumed cost of coal. ( 2006 \$)	\$42.11 per ton

Default values based on data in NETL 2007/1281 for LCOE from new IGCC plants with and without carbon capture. Thus the cost of carbon capture on retrofit IGCC plants may be more than this.

Make-up Power LCOE

Default:	12.5 cents/kWh	( 2010 dollars)
Custom (changeable):	6.4 cents/kWh	( 2007 dollars)

Defaults based on NETL 2007/1281 and Tawney, Khan, Zachary 2005

# Backup Slide: Power Costs Module Inputs - 2

## User Specified Cost Information:

- Display year for \$ amounts
- Capitalization factors
- Base LCOE (same as before)
- CO<sub>2</sub> capture, compression, and MUP costs
- CO<sub>2</sub> transport and injection costs
- Water extraction and transport costs
- Water treatment costs
- Brine disposal costs

WECSSim: a dynamic analysis tool

Summary      Power Plant      Carbon Capture      Carbon Sequestration      Extracted Water      Power Costs

**CO2 Pipeline Cost Parameters:**

Reference CO2 pipeline length	100 km
Reference CO2 pipeline flow rate	16,000 tonnes/da
Reference CO2 pipeline unit capital cost ( 2001 \$)	\$700 per m
Change to unit capital cost per change to length	0.24
Change to unit cost per change in flow rate	0.48
CO2 pipeline O&M as % of capital costs	4 %/yr

Default equation and values: Cost (Q<sub>0</sub>L) = \$700/m x (Q/Q<sub>0</sub>)0.48 x (L/L<sub>0</sub>)0.24  
from Ogden, J.M. (2002): Modeling Infrastructure For a Fossil Hydrogen Energy System with CO<sub>2</sub> Sequestration. Sixth Greenhouse Gas Control Technologies Conference, Kyoto, Japan, 9/30 - 10/4.

**Injection Well Cost Parameters:**

Fixed cost per injection well, Ogden method. ( 2001 \$)	\$1,250,000
Injection well variable costs by depth, Ogden method. ( 2001 \$)	\$1,560,000 per km

Default equation: Capital (\$/well) = \$1.56 million x well depth (km) + \$1.25 million.  
from Ogden, J.M. (2002): Modeling Infrastructure For a Fossil Hydrogen Energy System with CO<sub>2</sub> Sequestration. Sixth Greenhouse Gas Control Technologies Conference, Kyoto, Japan, 9/30 - 10/4.

**Water collection cost parameters**

Well field capital cost per depth and flow rate ( 2000 \$)	375 USD/ft/MGD
Percent of the cost above due to drilling only	75 %
Well pump efficiency (to estimate well energy use)	68 %
Wells other O&M as a function of capital cost	1.5 %/yr

Well field capital cost estimate from a regression of data shown in Figure 9-18 of "Desalting Handbook for Planners" 3rd Edition, July 2003, US Bureau of Reclamation Desalination and Water Purification Research and Development Program Report No. 72. <http://www.usbr.gov/pmts/water/media/pdfs/report072.pdf>  
Regression shown on page 62 and 63 of the June 1, 2009 report from SNL to NETL: "Study of the Use of Saline Formations for Combined Thermoelectric Power Plant Water Needs and Carbon Sequestration at a Regional Scale"  
Percent of cost due to drilling only, pump efficiency, and other O&M costs are model assumptions

**Water transport cost parameters**

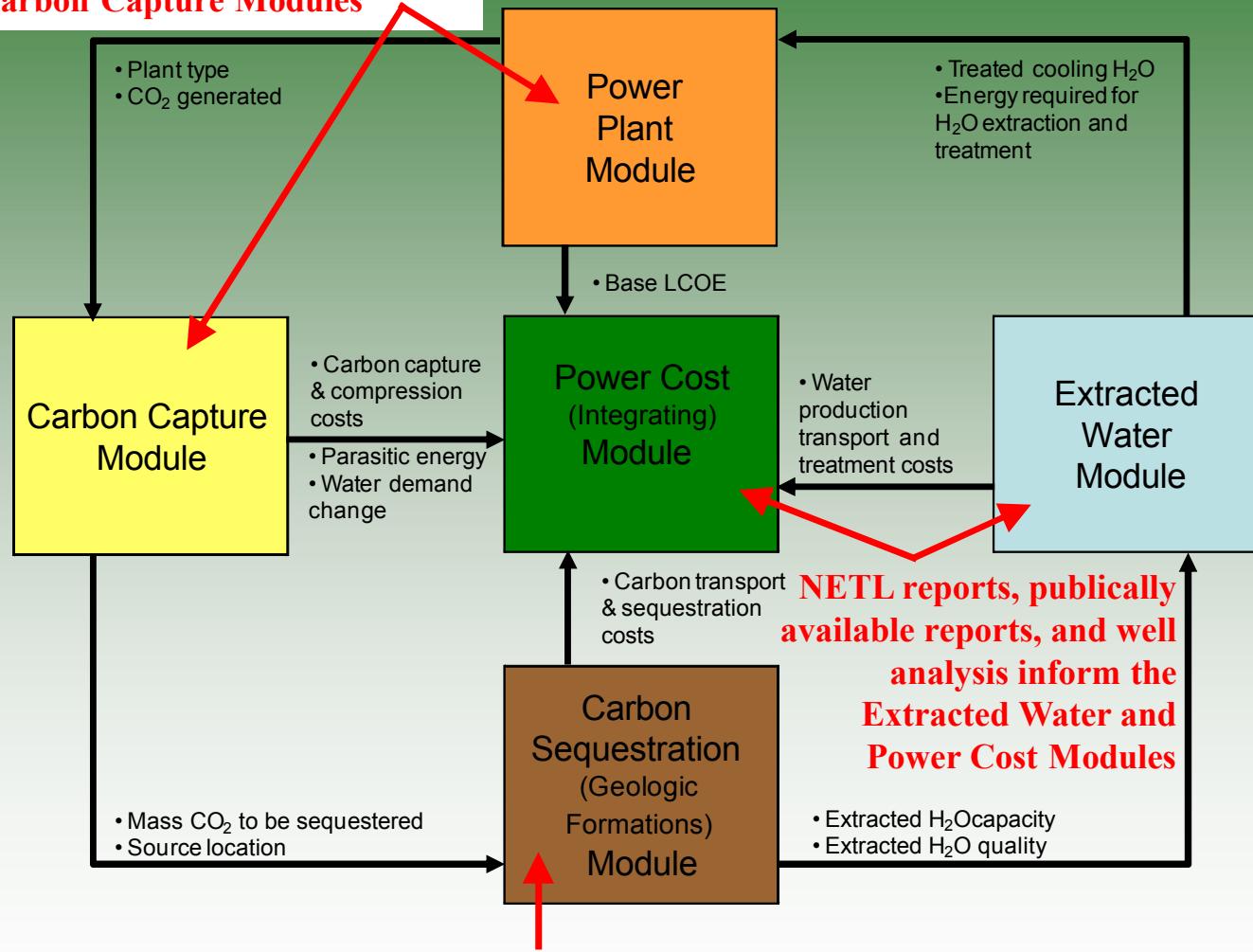
Pipeline base cost ( 2000 \$)	\$111,314 per mi
Pipeline marginal cost depending on flow rate ( 2000 \$)	35,761 USD/mi/MGD
Pipeline friction coefficient (for pipeline losses)	0.003
Pipeline pump efficiency	68 %

Pipeline capital cost estimates from a regression of data shown in Figure 9-11 of "Desalting Handbook for Planners" 3rd Edition, July 2003. US Bureau of Reclamation Desalination and Water Purification Research and Development Program Report No. 72. <http://www.usbr.gov/pmts/water/media/pdfs/report072.pdf>  
Pipeline friction and pump efficiencies are model assumptions.

**Input**

# Backup: WECSSim Modular Structure

Various NETL reports inform the Power Plant and Carbon Capture Modules



NatCarb Atlas polygon analysis, well data analysis, and heterogeneous formation characterization described above inform the Carbon Sequestration Module