

# 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**

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Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company,  
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Tenth Annual Conference on Carbon Capture & Sequestration



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

**(4) H<sub>2</sub>O Treatment & Use**



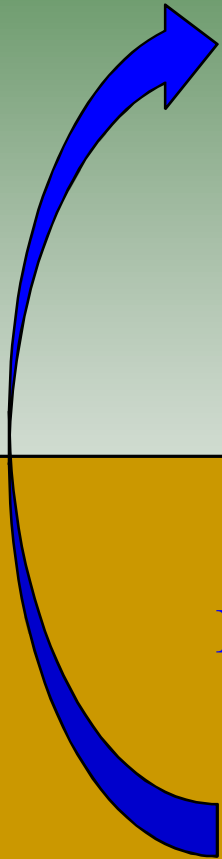
**(1) CO<sub>2</sub> Capture**



**(3) H<sub>2</sub>O  
Extraction**

**(2) Formation  
Assessment  
& CO<sub>2</sub> Storage**

Geologic Saline Formation



## 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:

2011

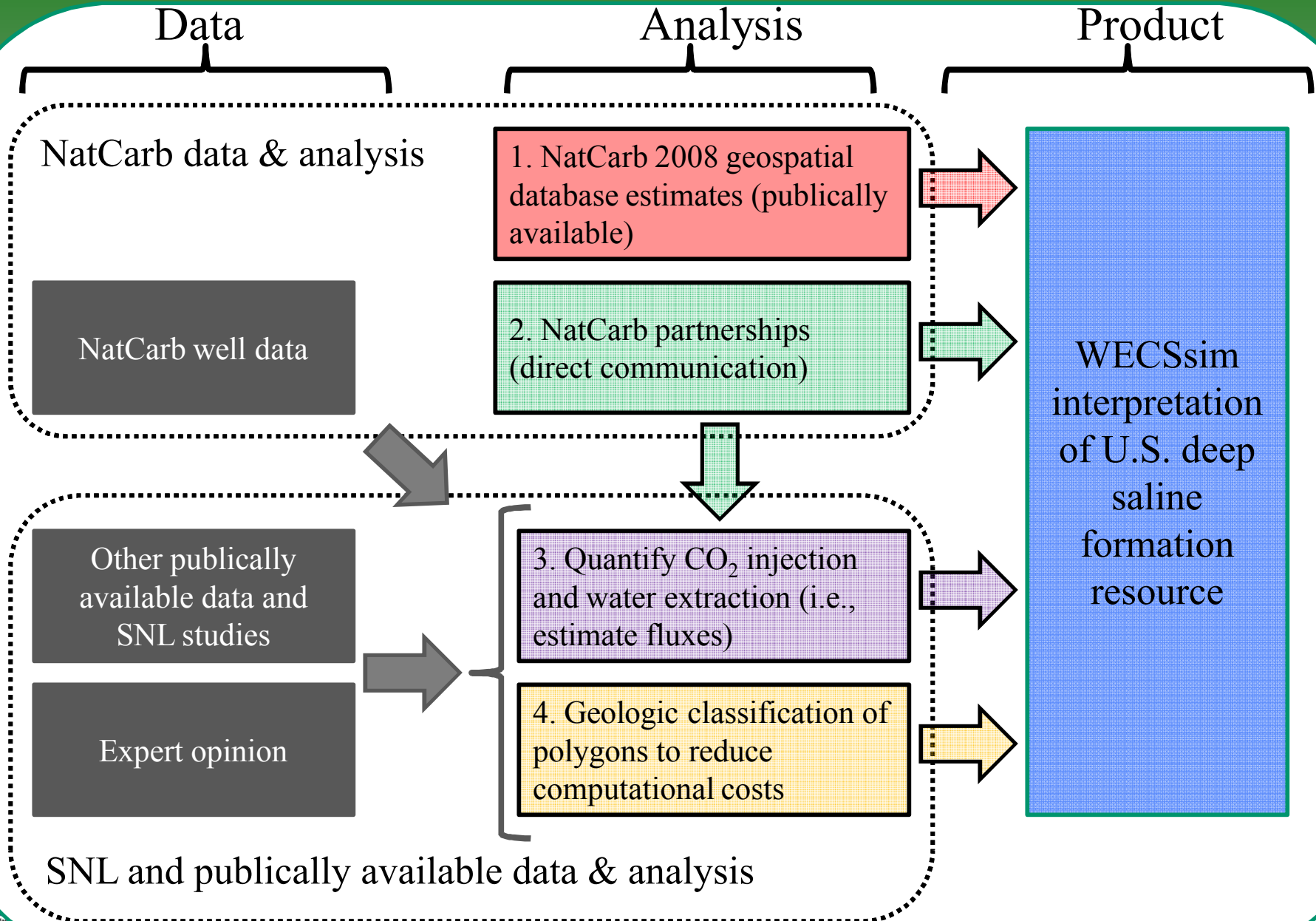
- Developed a single power plant to any saline formation sink in the U.S. systems calculator

2012

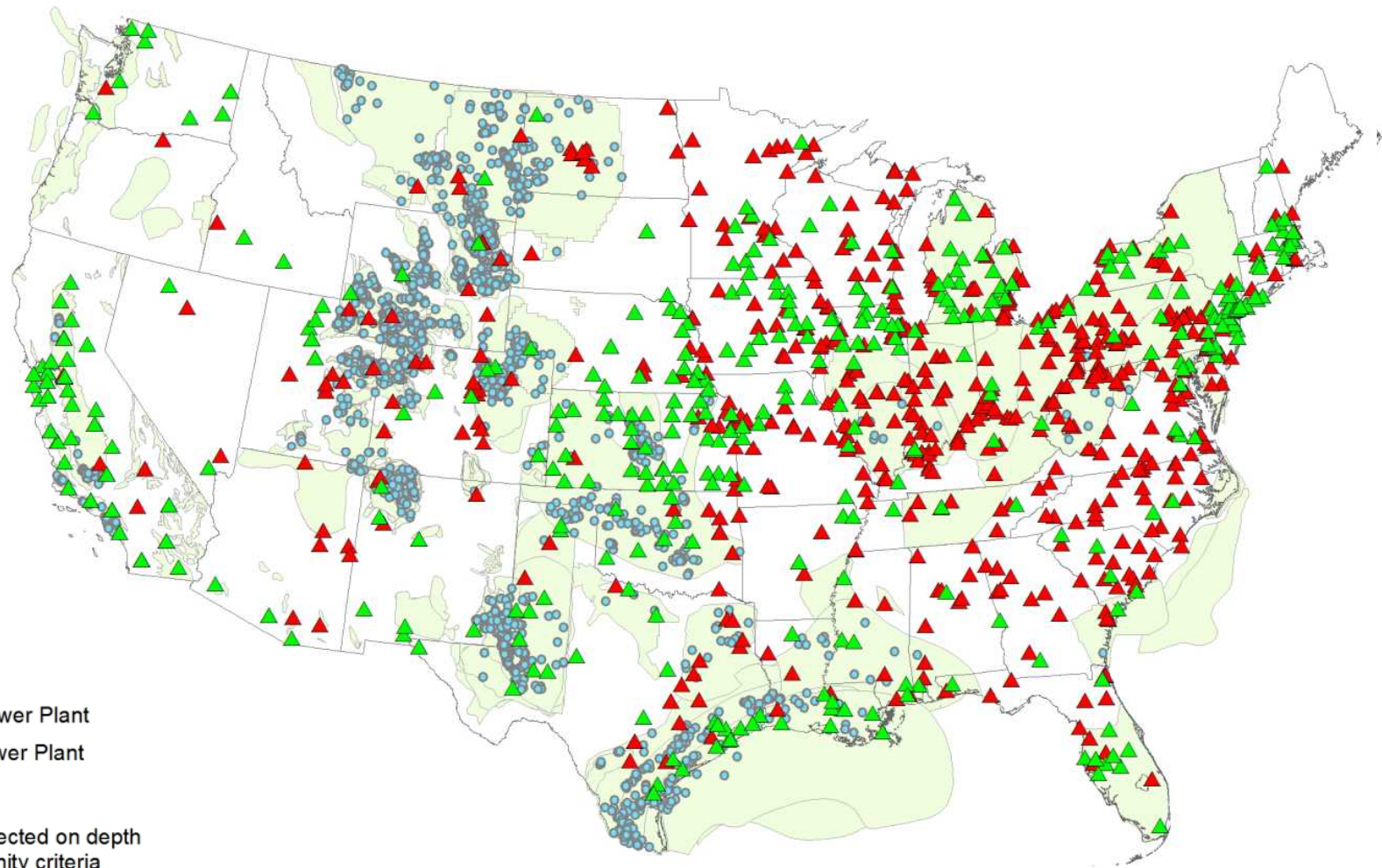
- **Phase IV & V:**
  - Expanding the role of uncertainty within the model

	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*



## Legend

▲ Coal Power Plant

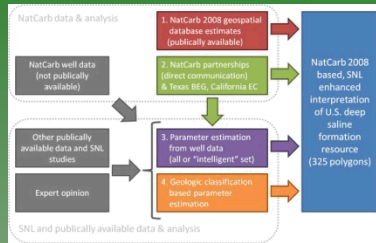
▲ Gas Power Plant

● Well

● Well selected on depth  
and salinity criteria

325 downselected formations from  
original NatCarb Atlas data

# Limited Saline Formation Data



Data availability by source for 325 polygons derived from NatCarb 2008

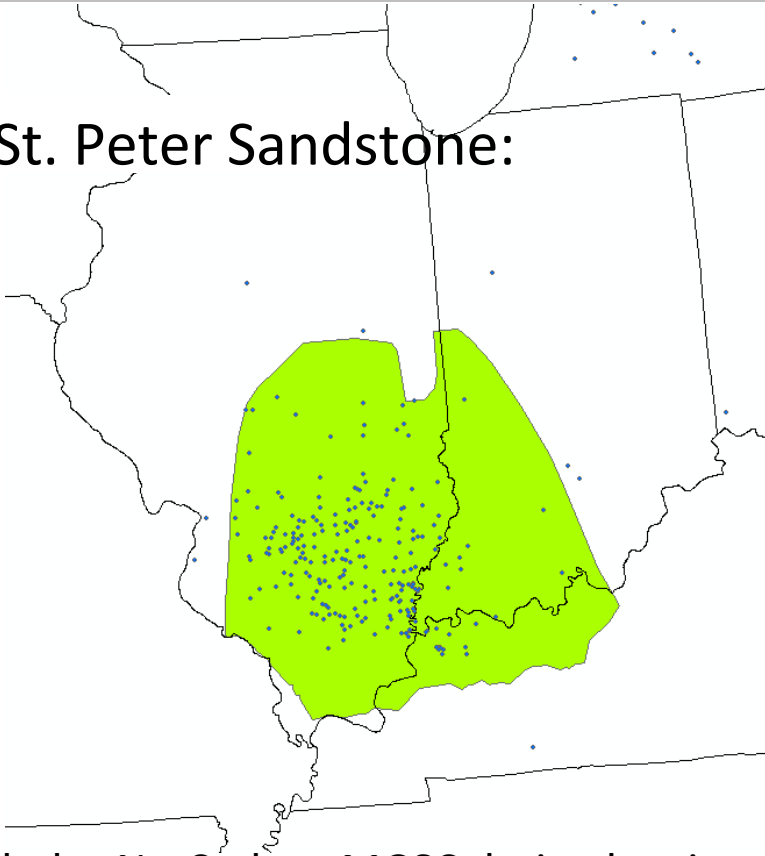
Data Source	CO <sub>2</sub> storage capacity	Area	Depth	Thickness	Porosity	TDS	Temp	Pressure
NatCarb 2008	42%	100%	0%	0%	0%	0%	0%	0%
Partnerships	42%	100%	62%	64%	55%	18%	44%	45%
Well records	NA	NA	70% <sup>1</sup>	70% <sup>1</sup>	0%	70% <sup>1</sup>	100% <sup>2</sup>	NA
Geologic class	NA	NA	NA	NA	? % <sup>3</sup>	0%	NA	NA
<b>No estimate</b>	<b>16%</b> (52)	<b>0%</b> (0)	<b>14%</b> <sup>4</sup> (47)	<b>14%</b> <sup>4</sup> (47)	<b>0 - 45%</b> (0 - 147)	<b>14%</b> <sup>4</sup> (47)	<b>14%</b> <sup>4</sup> (47)	<b>14%</b> <sup>4</sup> (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 publicly 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

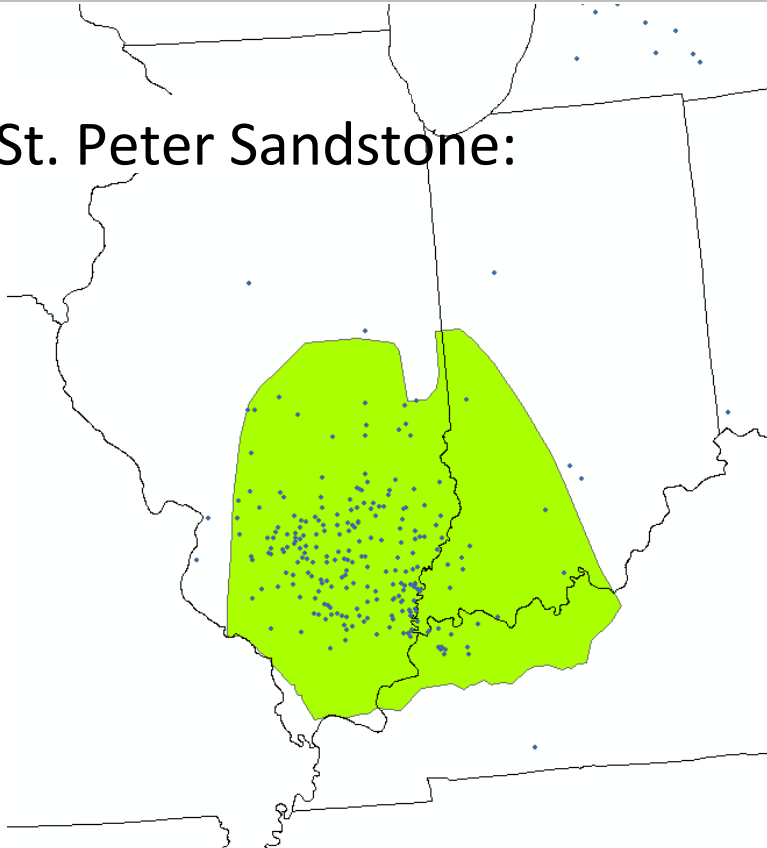
## St. Peter Sandstone:



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

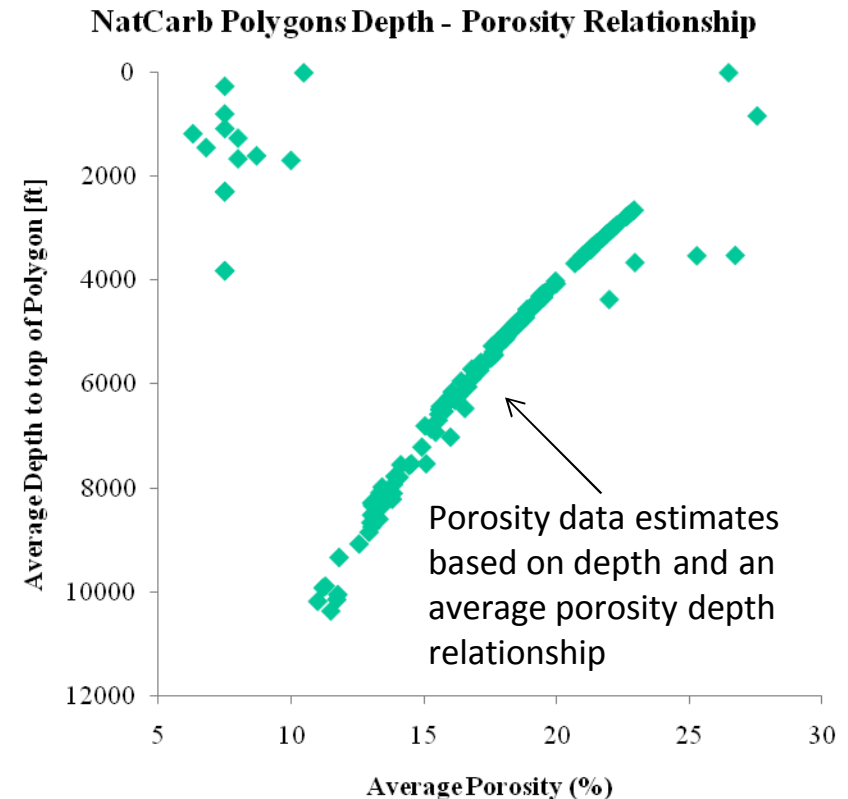
# Example formations: The good, but...

## 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.

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

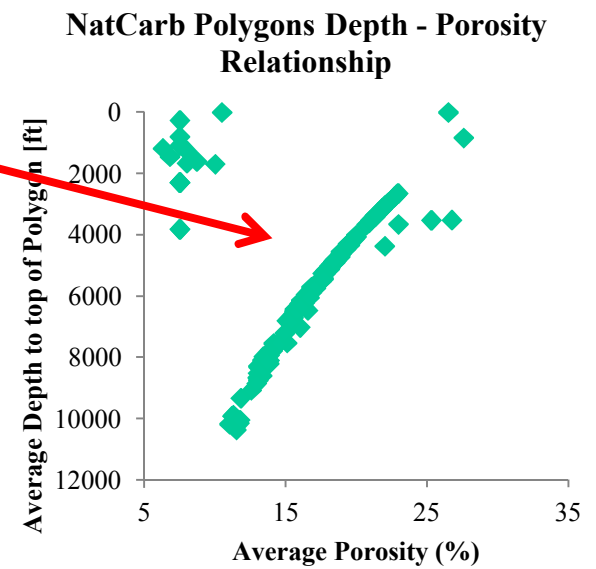
- From data analysis, recall that porosity data is limited
- Additionally, permeability/injectivity data is needed for economic analysis

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%		
Partnerships	42%	100%	62%	64%	55%	18%		
Well records	NA	NA	70% <sup>1</sup>	70% <sup>1</sup>	0%	70% <sup>1</sup>		
Geologic class	NA	NA	NA	NA	? % <sup>3</sup>	0%		
No estimate	16% (52)	0% (0)	14% <sup>4</sup> (47)	14% <sup>4</sup> (47)	0 - 45% (0 - 147)	14% <sup>4</sup> (47)		

Notes:

1. 30% of polygons (97 of 325) have no potentially intersecting wells associated with them from well databases used
2. Temperature calculated from depth and geothermal gradient. Geothermal gradient was developed spatially from
3. Current attempts to classify all 325 polygons according to geology may not result in reliable data estimates for all
4. 14% of polygons (47 of 325) have no depth, thickness, or salinity information and no potentially intersecting wells.



# Uncertainty and the Well Injectivity Index

$I$  well injectivity index;  
measure of the “ease”  
of injecting CO<sub>2</sub> into  
the well

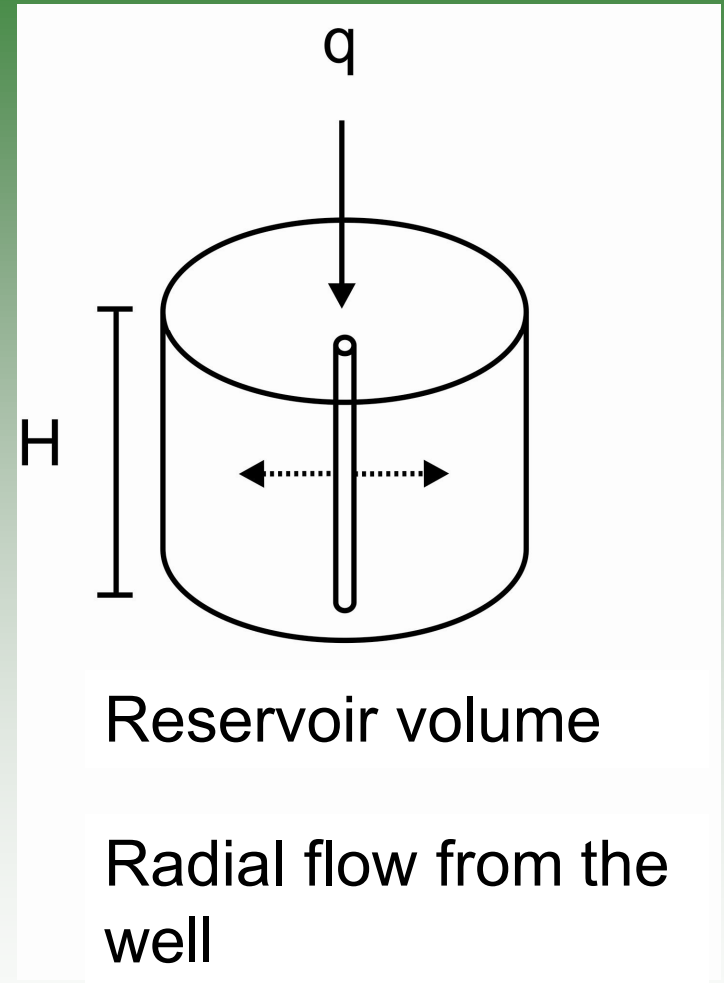
$$I \equiv \frac{q}{\Delta P}$$

$q$  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)

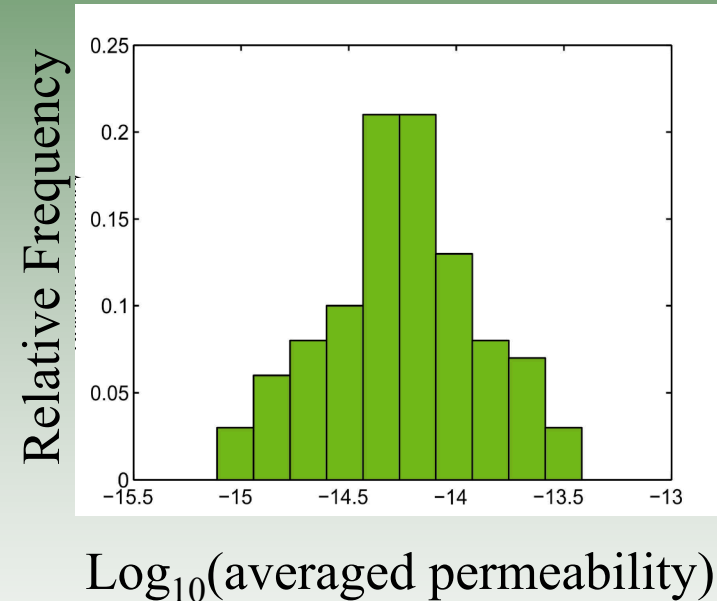
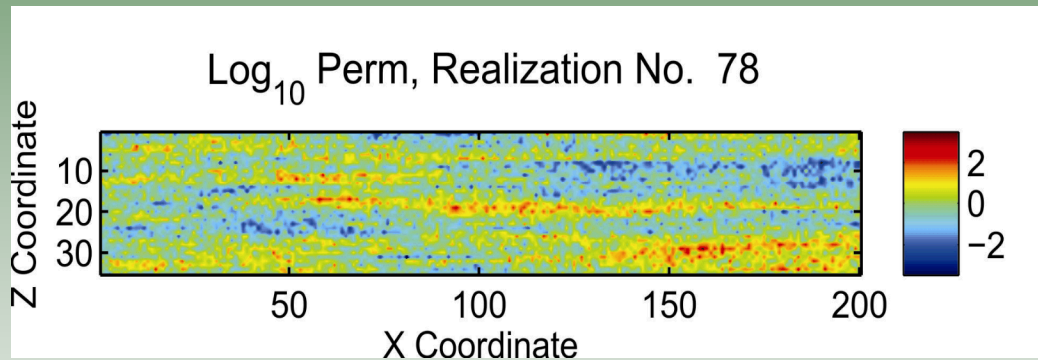


# Generating pdfs of Well Injectivity Index

Use geostatistics to generate multiple realizations of relevant parameter fields



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



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

WECSsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

### Selected Sequestration Formation

	Partnership	Basin Name	Formation Name
* Model Default	SECARB	Tuscaloosa Group	Tuscaloosa Group
Custom: (changeable with dropdown)	New (not in database)		
	Not in database	Not in database	Not in database

### Locations of Formation & Power Plant

Formation Location (centroid lat long, area average surface elevation)

	Latitude	Longitude	Surface Elevation
* Default	#####	-89°53'55"	203 ft
Custom (changeable)	36°	-108°	6,562 ft

Power plant to formation distance

* Default	0 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

Default shape from simplification of NatCarb 2d shape.

	NW	N	NE
Custom (changeable)	14 mi	13 mi	12 mi
	15 mi	Centroid	11 mi
	16 mi	17 mi	18 mi
	SW	S	SE

### Maximum distance power plant to default formation

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

0 50 100 150  
50 mi

### Formation Footprint Area

Default is based on geometry specified to the left.

* Default	46,521 mi <sup>2</sup>
NatCarb	56,326 mi <sup>2</sup>
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.

* Default	3,652 ft
Default source:	Texas BEG
Reported	3,652 ft
	Texas BEG
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.

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

Model Inputs may be Customized

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

## User Specified Saline Formation Info.:

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

WECSsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Model Default: SECARB  
Custom: (changeable with dropdown) Not in data

Locations of Formation & Power Plant Location

Formation Shape & Area

Approximate formation extent

Default shape from simplification of NatCabo 2d shape

Custom (changeable)

Sequestration Depth (below land surface)

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.

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

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

## Including Uncertainty:

- Temperature, pressure, CO<sub>2</sub> density
- Permeability, porosity, # of injection wells
- Odds of drilling a useable injection well (water quality related)
- Sweep efficiency
- Total storage resource

WECSsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Temperature at Sequestration Depth		Pressure at Sequestration Depth		CO <sub>2</sub> Density	
Default	45°C	Default	108 atm	Default	561 kg/m <sup>3</sup>
Custom (changeable)	50°C	Custom (changeable)	150 atm	Custom (changeable)	650 kg/m <sup>3</sup>

**Formation Permeability**  
Default estimated based on rock type and sequestration depth.

# Default distribution  
Custom distribution  
Custom single value  
51 mD

**Formation Porosity**  
Default calculated based on rock type and sequestration depth.

Default 0.11  
Custom (changeable) 0.15

**Injection wells required**  
Default based on maximum injection per well calculated from well & formation properties.

Default 18  
Custom (changeable) 5

**Odds of drilling a useable injection well**  
(Wells intersecting water with tds <= 10,000 ppm cannot be used for injection. Default odds based on % potentially intersecting well records with depths similar to sequestration depth and tds > 10,000 ppm.)

Default 99 % (All wells)  
Custom (changeable) 20 %  
5 % reduction in odds of drilling an unusable hole after each successful hole

**Sequestration Efficiency**  
(% of total pore space occupied by CO<sub>2</sub>)

0 20 40 60 80 100  
30 %

**CO<sub>2</sub> Storage Resource**  
Default calculated with formation area, thickness, porosity, sequestration efficiency, and co<sub>2</sub> density

Default	99,296 Mmt
NatCarb min	13,583 Mmt
NatCarb mid	33,958 Mmt
NatCarb max	54,332 Mmt
Custom (changeable)	50,000 Mmt

**Default Effective Permeability Distribution**

**Custom Effective Permeability Distribution (Model will normalize to get frequency sum of 1)**

**Useable bore hole learning curve**

# 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


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	Longitude	Elevation
30°	-94°	4 m

(click #s to change)

**Installed Capacity**

← 0 1,000 2,000 3,000 4,000 →

1,848 MW

**Capacity Factor**

← 0.0 0.2 0.4 0.6 0.8 1.0 →

0.72

**CO<sub>2</sub> Production Rate**

<input checked="" type="radio"/> Use default:	1,900 lbs/MWh
<input type="radio"/> Use custom:	2,200 lbs/MWh

(click # to change)

Default based on Exhibit ES-2 in NETL 2007/1281

**Expected Year Online and Offline**

	Start Yr	End Yr
<input checked="" type="radio"/> Existing plant	NA	2040
<input type="radio"/> New plant build	2010	2040

(click #s to change)

**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:	670 gal/MWh	520 gal/MWh

(click # to change)

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:	6.4 cents/kWh	2 cents/kWh	0.2 cents/kWh	4.2 cents/kWh	2007

(changeable)

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

# 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

WECSsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

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

**% CO<sub>2</sub> to be Captured**

100  
80  
60  
40  
20  
0

90 %

Parasitic energy requirements (from slider above and graph at right): 30 %

**Parasitic Energy Costs of Carbon Capture & Compression (CCC) (as % of Net Power Plant Production without CCC)**

50  
40  
30  
20  
10  
0

0% 30% 50% 70% 90% 100%

CO<sub>2</sub> Captured [%]

Parasitic Energy Cost [%]

default values (use defaults)  
custom values (click & drag to change) (use custom)  
values for PC retrofit from NETL Report 401/110907  
value for NGCC new from NETL/Parsons Feb 2002 Report  
value for IGCC new from NETL/Parsons Feb 2002 Report  
value for IGCC new from NETL/EPRI Dec 2000 Report

Power Plant Type:  
Pulverized coal subcritical

### Make-up power characteristics:

Model treats make-up power as if it is generated on site, and thus any carbon captured in makeup power production is added to the amount captured at the original plant for sequestration.

**Make-up PowerSource**

# Default: Coal: PC Subcritical  
Custom: Coal: PC Supercritical

**Make-up Power CO<sub>2</sub> Capture %**

# Default: 90 %  
Custom: 0 %

**Make-up Power Cooling Type**

# Default: Cooling tower(s)  
Custom: Cooling tower(s)

**Make-up Power LCOE**

# Default: 12.5 cents/kWh (2010 dollars)  
Custom: 6.4 cents/kWh (changeable) (2007 dollars)  
Default based on NETL 2007/1281 and Tawney, Khan, Zachary 2005

**Make-up Power CO<sub>2</sub> Generation**

# Default: 1,900 lbs/MWh  
Custom: 2,200 lbs/MWh (changeable)  
Default based on Exhibit ES-2 in NETL 2007/1281

**Make-up Power H<sub>2</sub>O Withdrawal**

# Default: 670 gal/MWh  
Custom: 530 gal/MWh (changeable)  
Defaults based on NETL 400/2008/1339 and NETL 402/080108

### Additional H<sub>2</sub>O needs due to CO<sub>2</sub> capture & compression (CCC)

Added H<sub>2</sub>O Withdrawals Rate per Mass CO<sub>2</sub> Captured at Original Plant Due to CO<sub>2</sub> Capture & Compression Processes (due mostly to cooling needs of compression)

# Use default: 298 gal/tonneCO<sub>2</sub> captured  
Custom: 300 gal/tonneCO<sub>2</sub> captured (click # to change)

Default based on interpretations of NETL 402/080108 and 2007/1281

# 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) 0 10 20 30 10 ppt

Max useable TDS (highest salinity treated in model) 0 50 100 30 ppt

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 reinjected brine (if any) added) 0 50 100 150 200 100 % = 5.45 MGD

Inputs dependent on sequestration formation selected:  
(Formation selected: SECARB 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)

# Default	30 %	(All wells)
Custom (changeable)	20 %	First well with 5 % reduction in odds of drilling an unusable hole after each successful hole

Useable bore hole learning curve

Expected holes drilled per extraction well

Rescale Axis

Extraction wells depth (default based on minimizing drilling costs resulting from probability of drilling a useable well)

# Default	2500' to 5000'
Custom (changeable)	4,725 ft

Average salinity from useable wells (average salinity of well records with acceptable TDS potentially intersecting selected formation)

# Default	22 ppt
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.)

# Default	-13 in/yr
Custom (changeable)	10 in/yr

Required evaporation pond area (Pond area required if brine is to be disposed of using evap ponds. ? means evap ponds won't work.)

# Default	? acre
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.))

# Default	66 mi
Custom (changeable)	0 mi

Elevation of free brine disposal point (Sea level by default)

0 50 100 0 ft

Inputs dependent on power plant and sequestration formation selected:

Number of operating extraction wells (Default based on formation thickness, porosity, and permeability.)

# Default	13
Custom (changeable)	4

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.)

# Default	0 mi
Custom (changeable)	0 mi

Selected Brine Disposal Method (Unlike other custom inputs, custom option here will not alter the model selected default formation.)

# Default	Transport and dump
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

WECSsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Input

### 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 DiFillipo 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

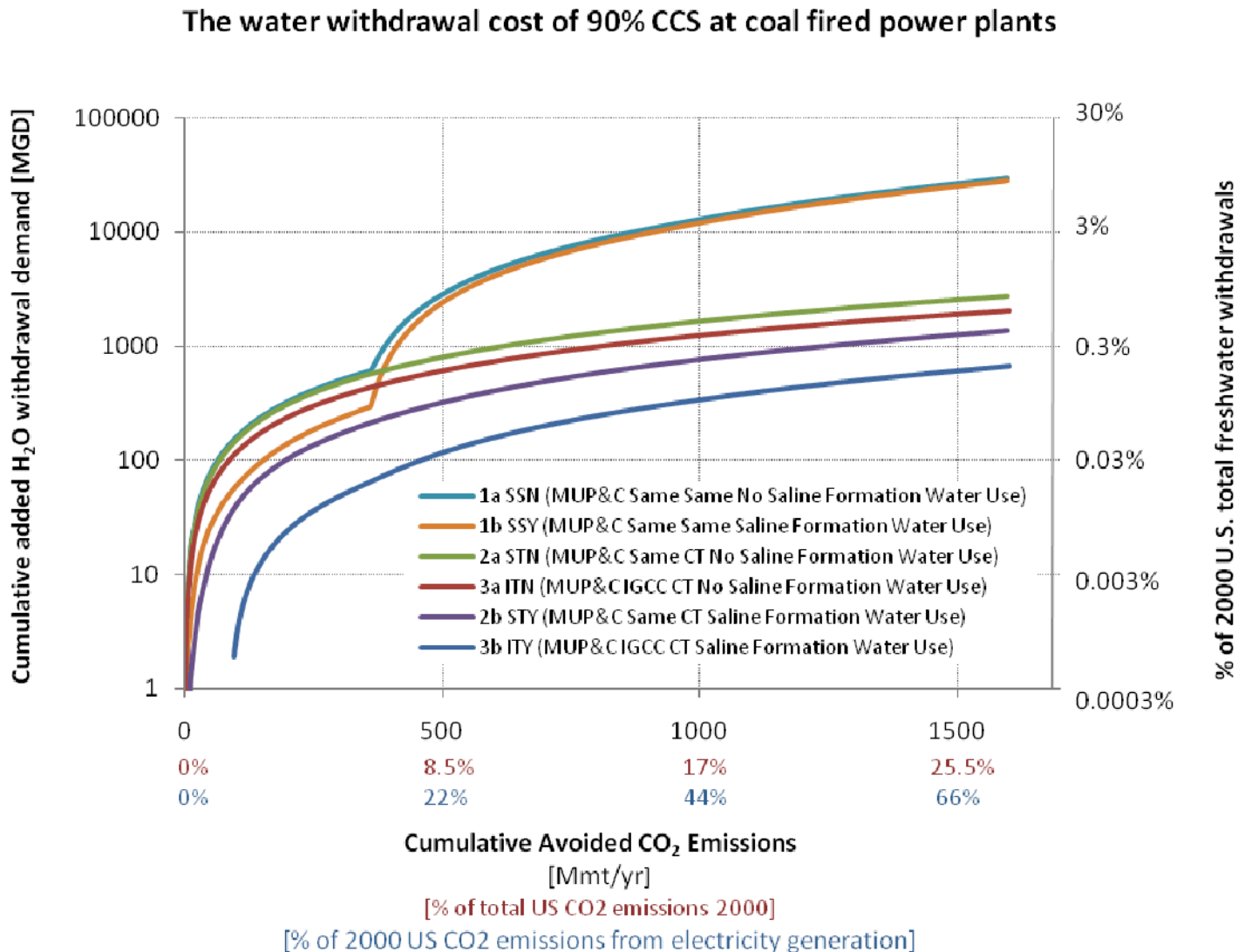
Evaporation ponds fixed capital cost:	\$19,600
Evaporation ponds variable capital cost:	\$244,900 per acre
Evaporation ponds O&M as % of capital cost:	1.5 %/yr
Injection wells fixed capital cost:	\$2,359,271
Injection wells variable capital cost:	\$194,893 per MGD
Injection pipelines and wells O&M as % 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.

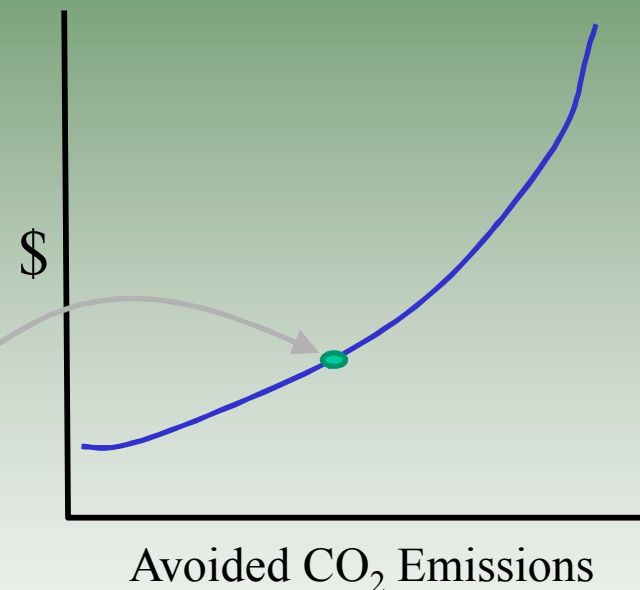
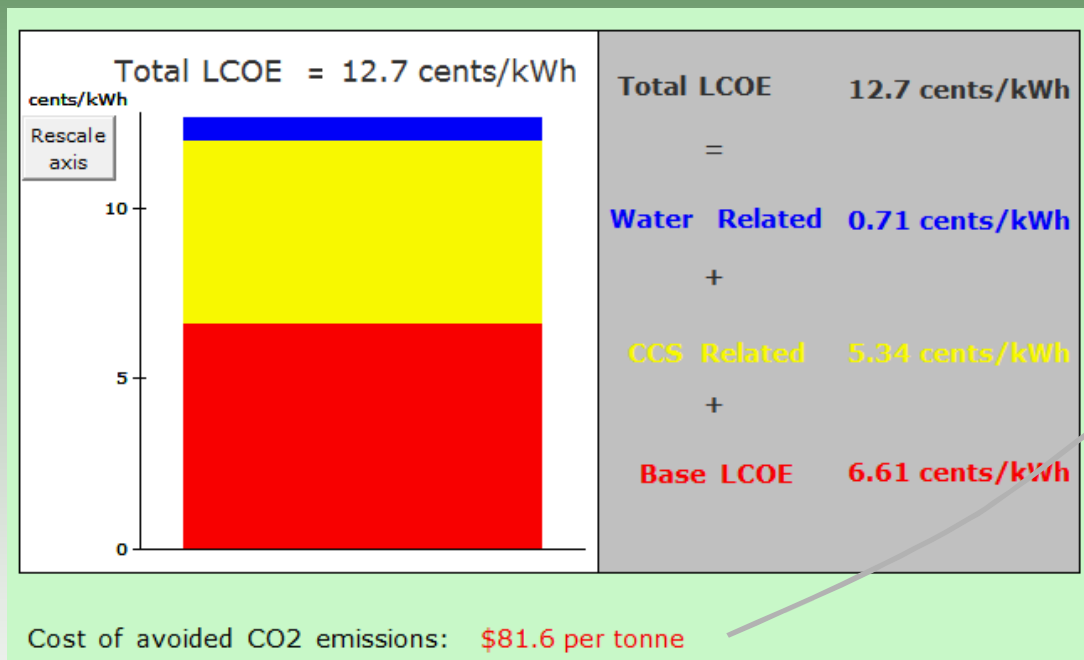
# WECSsim Results:

*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

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# 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

**Thank You.**

Peter H. Kobos, Jesse D. Roach, Geoff T. Klise, Jim L. Krumhansl,  
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Andrea McNemar, and Malynda A. Cappelle

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# Backup Slide: Power Costs Module Inputs

## 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

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WECSim: 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:
Default:	6.7 cents/kWh	= 2.1 cents/kWh	+ 0.3 cents/kWh	+ 4.4 cents/kWh	2010
Custom: (changeable)	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

CO2 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	$VO\&M[Thousands\ of\ 2006\$/yr] = 46.183 * CO2Captured[tonne/hr] + 1838.6$	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 CO2 captured. ( 2006 \$)	\$190 hr/lb
Selexol fixed O&M costs per CO2 captured. ( 2006 \$)	\$0.35 per tonne
Selexol variable O&M costs per CO2 captured. ( 2006 \$)	\$0.57 per tonne
Additional coal use at IGCC per CO2 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)

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

# Backup Slide: Power Costs Module Inputs - 2

## User Specified Cost Information:

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- CO<sub>2</sub> transport and injection costs
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- Water treatment costs
- Brine disposal costs

WECSsim: a dynamic analysis tool

Summary Power Plant Carbon Capture Carbon Sequestration Extracted Water Power Costs

Input

**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:  $\text{Cost (Q,L)} = \$700/\text{m} \times (\text{Q}/\text{Q}_0)^{0.48} \times (\text{L}/\text{L}_0)^{0.24}$   
from Ogden, J.M. (2002): Modeling Infrastructure For a Fossil Hydrogen Energy System with CO2 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:  $\text{Capital (\$/well)} = \$1.56 \text{ million} \times \text{well depth (km)} + \$1.25 \text{ million}$ .  
from Ogden, J.M. (2002): Modeling Infrastructure For a Fossil Hydrogen Energy System with CO2 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

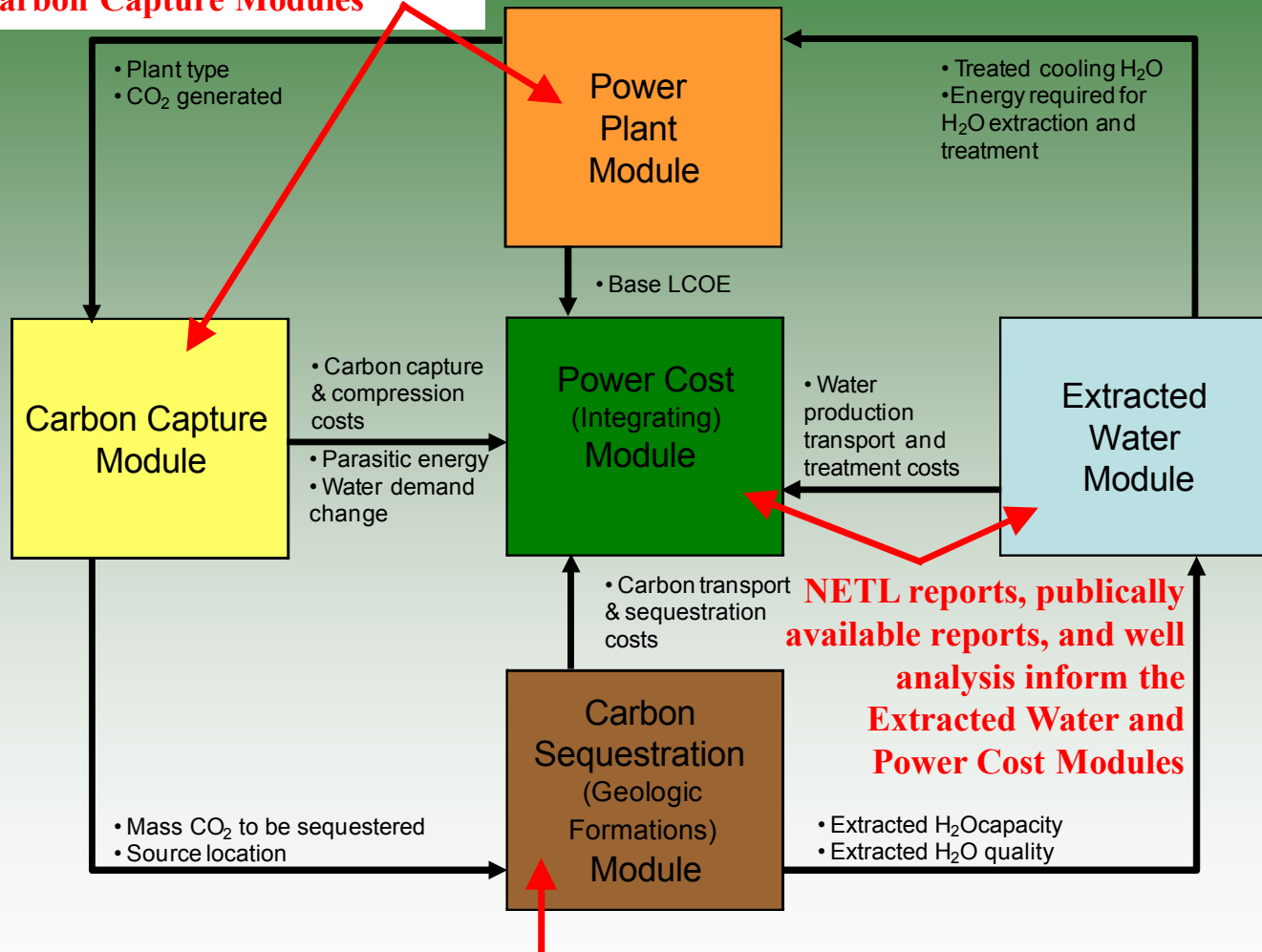
**Water transport cost parameters**

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.

# 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