



The String-of-Pearls

An Overview of the Integrated Assessment Model

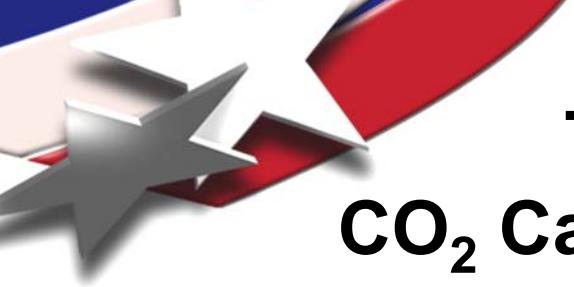
**Peter H. Kobos
Leonard A. Malczynski
David J. Borns**

Sandia National Laboratories
&
The Southwest Regional Partnership for Carbon Sequestration

National Energy Technology Laboratory
Modeling Tutorial Workshop
Pittsburgh, Pennsylvania
March 7, 2007

 Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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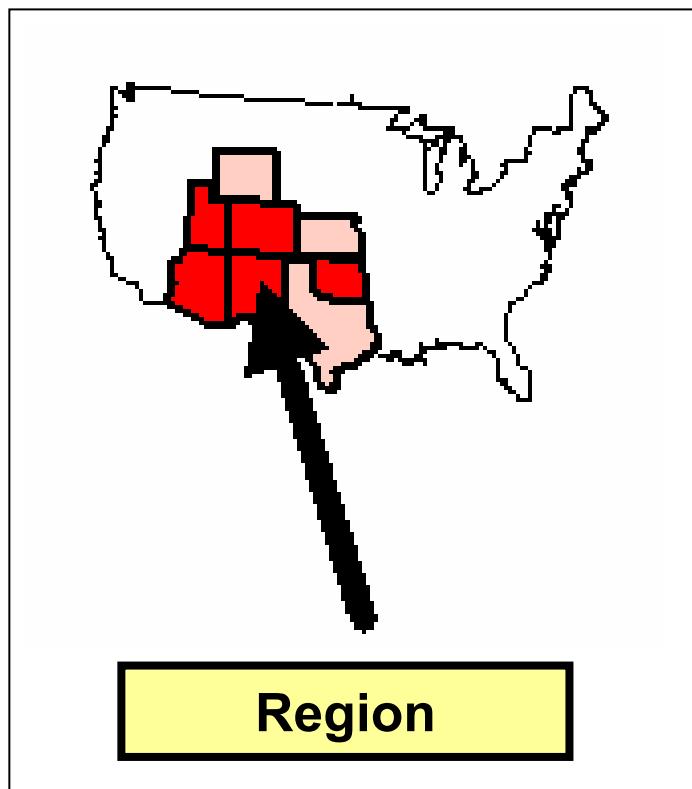


The Integrated Assessment Model: CO₂ Capture, Transportation and Storage

1. Characterize the physical, economic and policy requirements for a carbon sequestration project
2. Develop a high-level methodological framework for analysis
3. Build an Integrated Assessment model (a dynamic simulation computer model in *Powersim Studio*) to help interested parties understand the potential screening criteria necessary to develop such a project
4. Apply the model to the Southwestern United States, and beyond



The Integrated Assessment Model: Attributes and Screening Criteria



- Model characterizes the screening criteria:
 - Underground geologic storage of carbon dioxide (CO₂)
 - CO₂ Source and Sink Matching
 - Costs associated with this system
 - Expanded to include Regional Totals



Progress of the Integrated Assessment Modeling Efforts

Timeline

2004

- **Completed:**
 - Developed a Test Case Model
 - » 'systems view' in the SW Regional Partnership
 - » A few sources and sinks in New Mexico to set the framework

2005

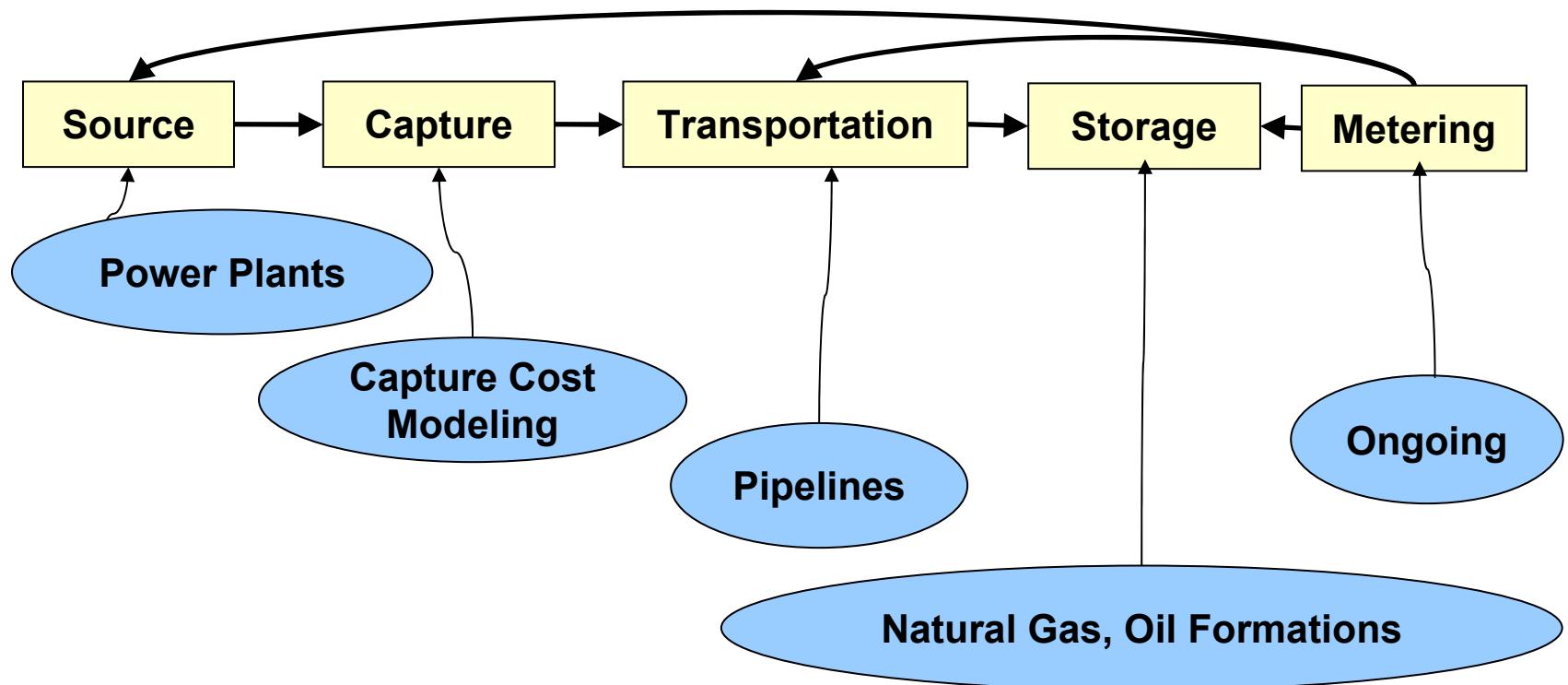
- **Completed:**
 - Employing the String-of-Pearls Beta 1.0 model algorithms
 - Develops a CO₂ sequestration network in the full SW Region
 - » (CO₂ sources, pipelines, sinks)

2006

- **Where we are:**
 - Refine Regional Totals (CO₂, Cost, CCS potential)
 - Include a financial payback model for CCS technology
 - Develop a website to access SNL CCS resources
 - Investigating a cost optimization module to find the least cost solution for a Carbon-constrained future in the SW



Schematic of the Integrated Assessment Model



Systems Cost =

Capture Cost t_{CO_2} + Pipeline Cost t_{CO_2} + Surface Piping and Well Costs t_{CO_2} + Measurement, Monitoring and Verification t_{CO_2}



Carbon Capture, Transportation, and Storage Equations

Systems Cost =

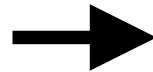
Capture Cost t_{CO_2} + Pipeline Cost t_{CO_2} + Surface Piping and Well Costs t_{CO_2} + Measurement, Monitoring and Verification t_{CO_2}

- **Carbon Capture**
 - Based on IECM model results provided by GTI, developed into a regression for coal and gas plants captured for the interim, as the working group standardizes the equations and metrics:
 - (\$/ton CO₂ captured):
 - » $Cost_{coal} (\$/ton) = 48.9683 + (0.0003 * MW) + (-0.2030 * \% \text{ capture of CO}_2)$
 - » $Cost_{natural\ gas} (\$/ton) = 117.6814 + (0.0409 * MW) + (-0.6665 * \% \text{ capture of CO}_2)$
 - (\$/MWh with CO₂ captured):
 - » $Cost_{coal} (\$/MWh) = 70.4104 + (-0.0097 * MW) + (0.4873 * \% \text{ capture of CO}_2)$
 - » $Cost_{natural\ gas} (\$/MWh) = 87.3710 + (0.0346 * MW) + (0.0346 * \% \text{ capture of CO}_2)$
- **Transportation**
 - Based on Joan Ogden (2002) (UC Davis) and Bob Williams (2002) (Princeton)
 - » $Cost \text{ of the pipeline transmission } (\$/tCO_2)_{coal, natural\ gas} =$
 $Capital\ Cost_0 * (Quantity_n / Quantity_0)^{-0.53} * (length\ of\ pipeline / length\ of\ pipeline_0)^{1.24}$
- **Surface Piping and Disposal Wells**
 - Based on Joan Ogden (2002) (UC Davis) and Bob Williams (2002) (Princeton)
 - » $Cost \text{ of surface piping near the disposal wells } (\$/tCO_2) =$
 $0.138 * (Quantity\ of\ CO_2 - 104.17)^{0.253}$
 - » $Cost \text{ of disposal wells } (\$/well) = \$1.0 \text{ million} + (\$1.25 \text{ million/km}) * [\text{depth of well (km)}]$
- **Monitoring, Measurement and Verification**
 - Range Based on Benson et al. (2004)
 - » $\$0.16 \text{ to } \$0.31 \text{ per tonne of CO}_2$

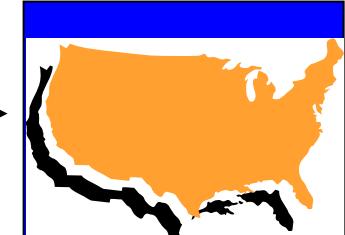
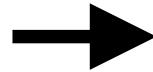


Expandability: The Model Can Accommodate More Data.

SW Data Model SWP Results Model Interface



Other States Same Model U.S. Results Larger Interface
= More Data



Integrated Assessment Website: Developing another way to collaborate

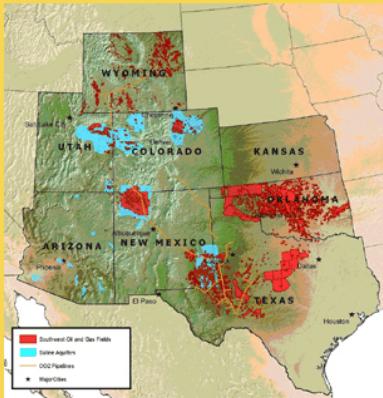
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Carbon Sequestration

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 String of Pearls

The Integrated Assessment Cost and Source-Sink Model



This research describes the 'String of Pearls' analytical model used by the Southwest Regional Partnership on Carbon Sequestration to assess potentially hundreds of carbon dioxide (CO₂) source and geological sink combinations in the Southwestern United States. The model can help decision makers (e.g., policy analysts and interested companies) determine where a power plant (or other CO₂ source) could be built given a set of planning decisions based on current power plant locations, sink availability, and existing pipeline infrastructure right-of-ways.

The working results indicate that the cost of capturing carbon dioxide is by far the majority of a project's overall capital cost. The analysis also develops overarching regional CO₂ sequestration totals and relative costs, and sink lifetimes across an initial fifty-year time horizon. The region may support anywhere from several decades to several thousand years' worth of sink capacity.

[Questions & Comments](#) | [Privacy and Security](#)
Last modified: March 1, 2007

The Integrated Assessment Model and 'The String of Pearls'

SWP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Base Case English (United... 15... ?

WYOMING

Salt Lake City UTAH

ARIZONA NEW MEXICO

Phoenix Albuquerque Lubbock Dallas

Sandia National Laboratories

Southwest Regional Partnership On Carbon Sequestration Integrated Assessment Model: The String of Pearls

DAVID J. BURNS PETER H. KOBOS LEONARD A. MALCZYNSKI

Beta Version

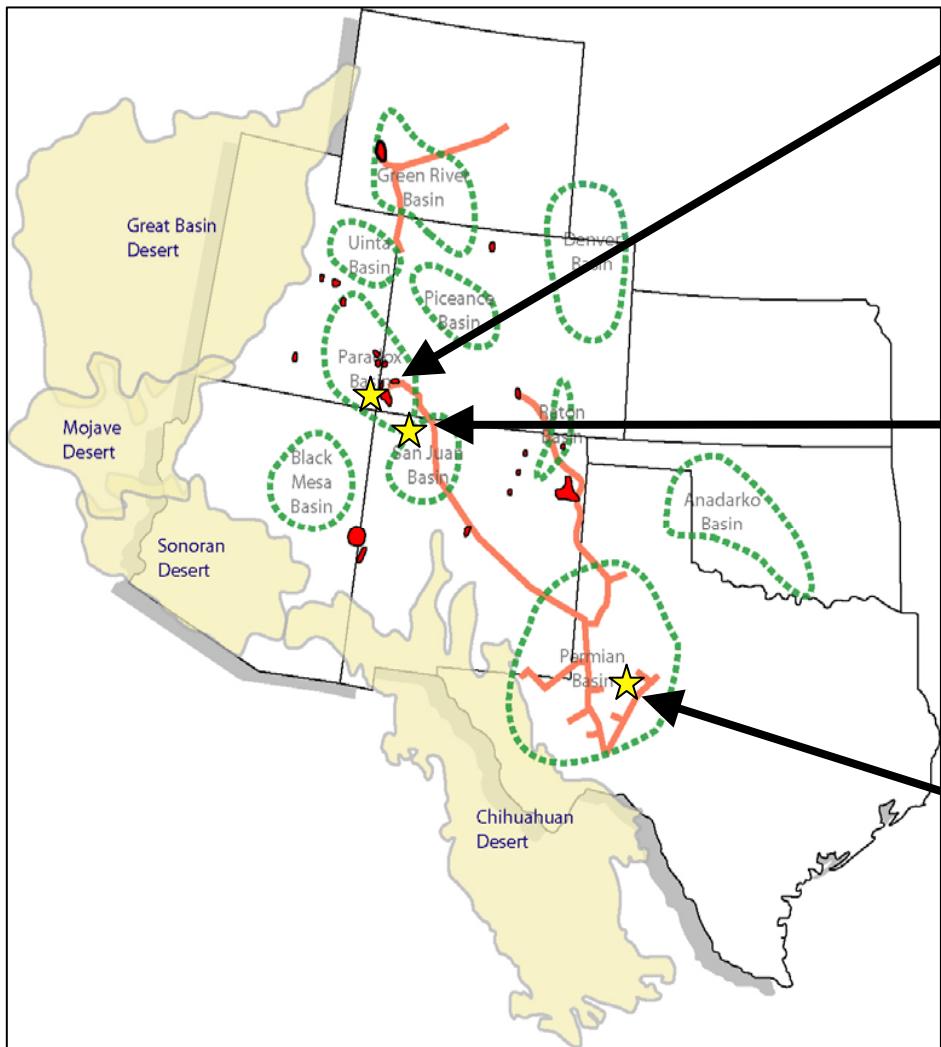
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Click Here to Continue

01/01/2000



Phase II Demonstration Options: Geological Sequestration



- Paradox Basin, Utah: combined EOR and deep saline aquifer sequestration pilot test
(Jim Rutledge)
- San Juan Basin, NM: combined ECBM and terrestrial sequestration pilot test
(Scott Reeves, Joel Brown)
- Permian Basin, TX: combined EOR and sequestration pilot test at SACROC & Claytonville
(Mark Holtz)



Concluding Remarks and Issues to Address in the Assessment

- **Carbon Model Issues**

- Findings: majority of the total cost (~90%) is with capturing the CO₂
 - Ongoing: development for time scale, projections, costs, granularity issues

- **Regional Allocation**

- Lessons: Source sink combinations coordinated across states and basins
 - Barriers: Economic and Regulatory issues by political boundary, Sources and Sinks traverse political boundaries

- **Sources of Carbon**

- Currently: The model includes power plants
 - Ongoing: Utility vs. Non-Utility, Potentially Locate New Plants



How the SW Partnership can Collaborate with the Other Partnerships

- **Demonstrate the String-of-Pearls model**
 - for collaborative modeling assessment
- **Include cost metrics**
 - developed by the CCS Working Group
- **Looking to collaborate via a website**
 - established for the SW Partnership members, and others, to assess the model
- **Analyze Performance and Economic Risk**
 - Sandia Labs is also part of the risk assessment team in the SW Partnership



New Model Developments

- **Regional Totals:**
 - Phase I and Part of II were tasked for single source to sink, now assessing the totals
- **Including Time:**
 - Financial assumptions, dynamic sink lifetime
- **Flexible Model, can incorporate the Working Group's standardized economics CCS:**
 - e.g., a general plant type's engineering, economic and lifetime metrics, => \$/kWh with and without CO₂ capture



Future Modeling Efforts

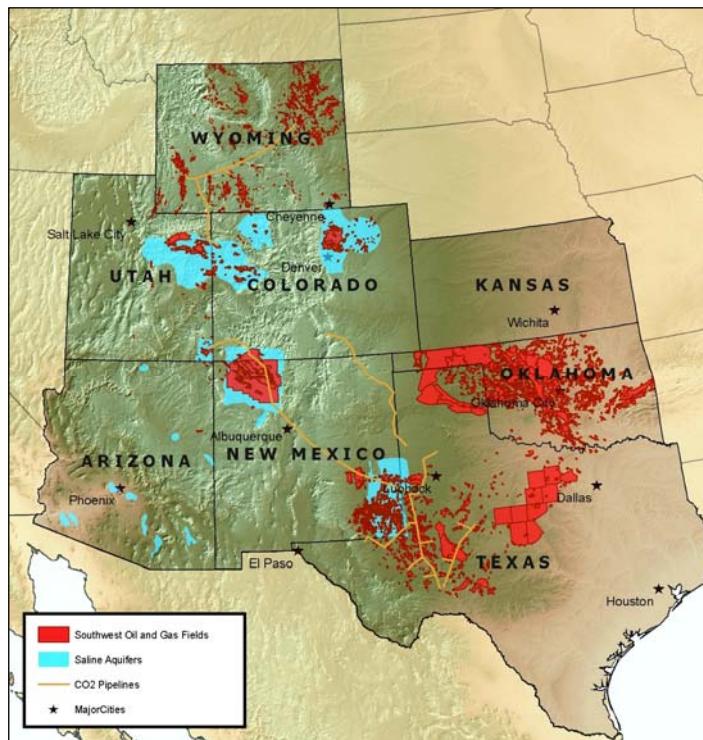
- **Focus on demonstration test cases**
- **Add additional plant characteristics**
- **Coordinating with other Regional Partnerships to tell a more ‘seamless story’ with respect to the analytical efforts (e.g., costs)**
- **Investigating the develop of a linear programming capability within the model (e.g., least cost solution)**
- **Ongoing iterative Partnership feedback**
 - » Workshops, One-on-one, Web-based sessions, teleconferences (CCS, MMV)
 - » Management Feedback, resource allocation (time, \$)



The String-of-Pearls

An Overview of the Integrated Assessment Model

Thank You



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Appendix: The String of Pearls Model's Working Interface



Appendix: The String of Pearls Model's Working Interface

SWP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Home String of Pearls Systems Results Maps Sandia National Laboratories

The String of Pearls: The model calculates the shortest distance from a power plant (CO₂ source) to the sinks.

The Sinks are Nodes 1 - 10. (Picture Orientation and Size Not to Scale)

01/01/2050

Appendix: The String of Pearls Model's Working Interface

SWP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Home String of Pearls Systems Results Maps Sandia National Laboratories

The String of Pearls: Choose a CO2 source (Coal, Gas, Custom), and watch or select the String of Pearls sinks.

Source: Select a Source

Use selected Source (e.g., San Juan)
 Use custom Source (e.g., Lat., Long.)

NM-SAN JUAN, COAL: 1779 MW (Default)

Sinks: Select from the database of Sinks

Arizona Coal Bed Methane
 Colorado Oil/Gas
 New Mexico Saline Aquifer
 Oklahoma Pipelines
 Utah

Maximum Distance from Source (km)
1,000

Minimum Capacity of Sink (mmtonnes)
0

Sink(s): Automatic String of Pearls, or Custom Sink Option

Region CO2 Totals Plant Assumptions Other

Electricity 9.70 cents per kWh Note: illustrative electricity cost only

Power Plant	Plant	Sink	Distance (km)	Cost (\$/tonne)
Selected	14		24.5	36
Sinks	from Sink	to Sink	Distance (km)	Cost (\$/tonne)
	14	39	19.1	36
	39	40	2.2	35
	40	24	54.4	37
	24	41	5.0	35
	41	42	0.7	36
	42	43	7.9	36
	43	54	38.0	37
	54	51	22.8	37

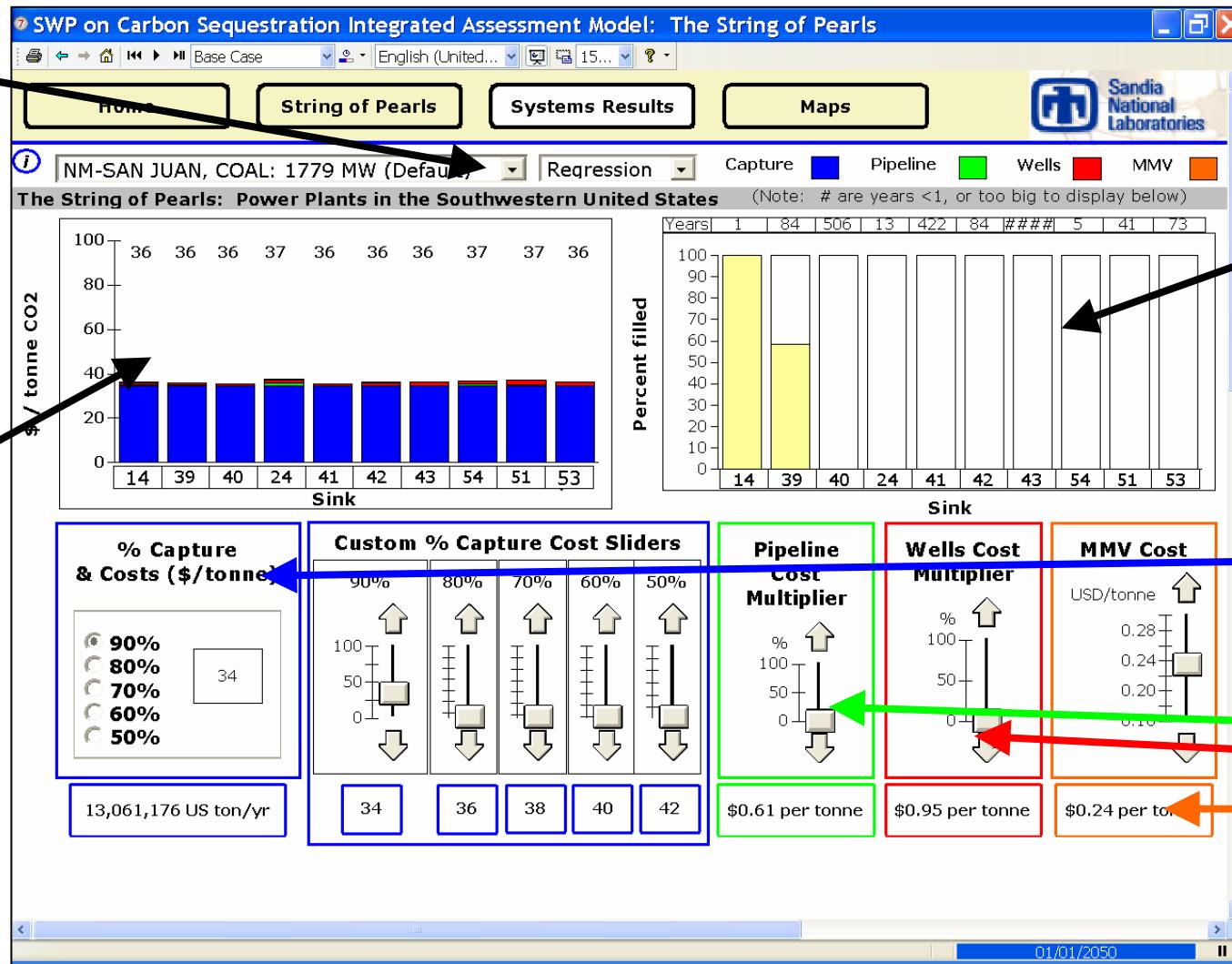
Note: The "0" for a Sink indicates the end of the string of pearls.

Click here to Select Specific Sinks

Click here to Show Regional Perspective

01/01/2050

Appendix: The String of Pearls Model's Working Interface



Years of Useful Sink Fill Time

Users can Adjust the:

- % of CO₂ captured
- costs to capture CO₂
- pipeline cost
- Well costs
- Baseline MMV cost.

Select the Specific Power Plant in the SW U.S.

Stacked systems costs

Appendix: The String of Pearls Model's Working Interface

SWP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Home String of Pearls Systems Results Map Sandia National Laboratories

Information: Additional Source Options and Sink Information

The Integrated Assessment model's underlying CO₂ flow and cost model structure.

Source:
Select the Location of the Custom Power Plant

Latitude: 36.00
Longitude: -104.00

Sink(s):
Automatic String of Pearls, or Custom Sink Option

Pipeline Capacity as a Sink

Note: Nodes above 219 in the "String of Pearls" screen are part of existing pipelines

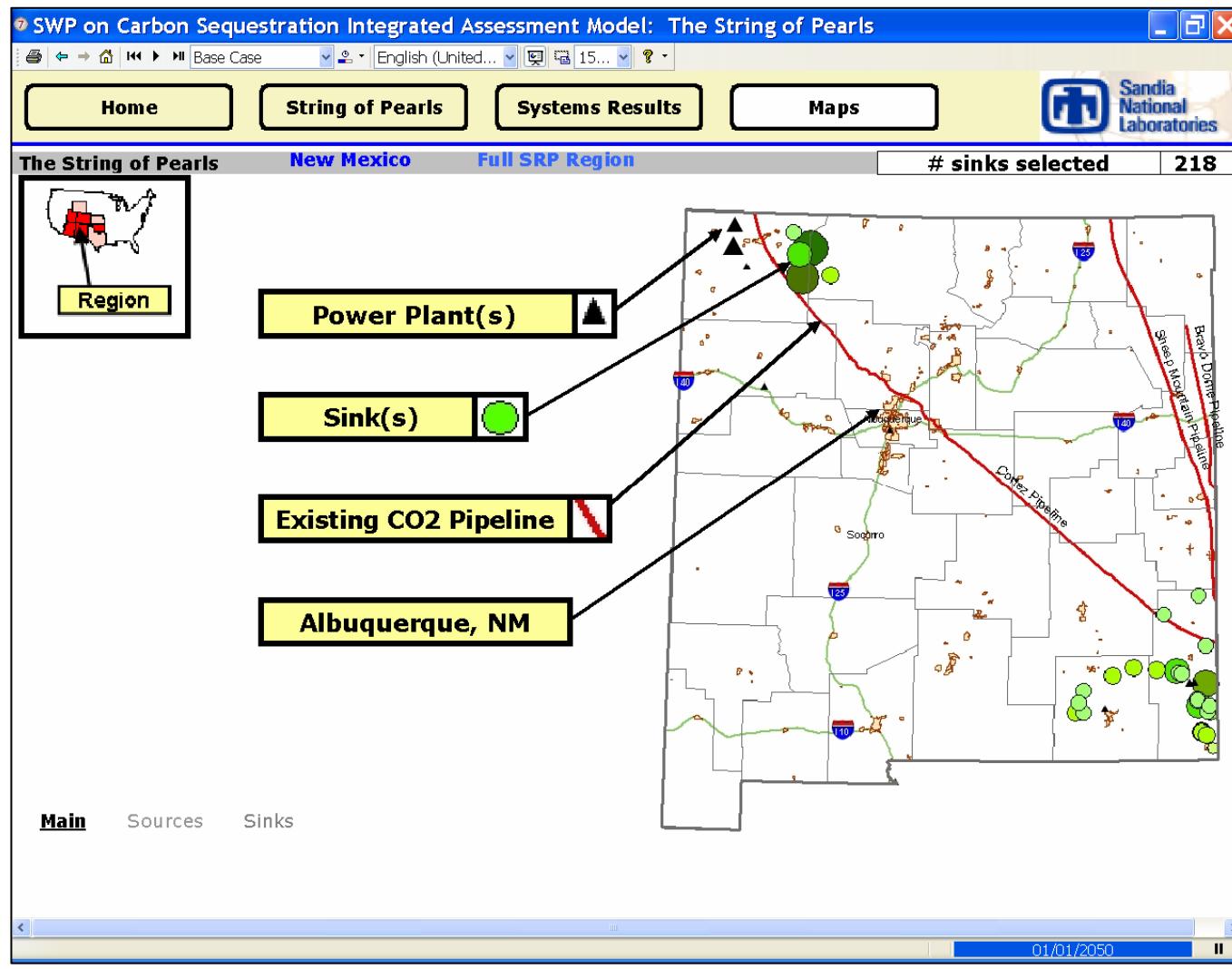
Additional criteria under development.

1,000 million metric tons

million metric tons
10,000
5,000
0

01/01/2050

Appendix: The String of Pearls Model's Working Interface



Appendix: The String of Pearls Model's Working Interface

SWP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Base Case | English (United States) | 15... | ? | Home | String of Pearls | Systems Results | Maps | Sandia National Laboratories

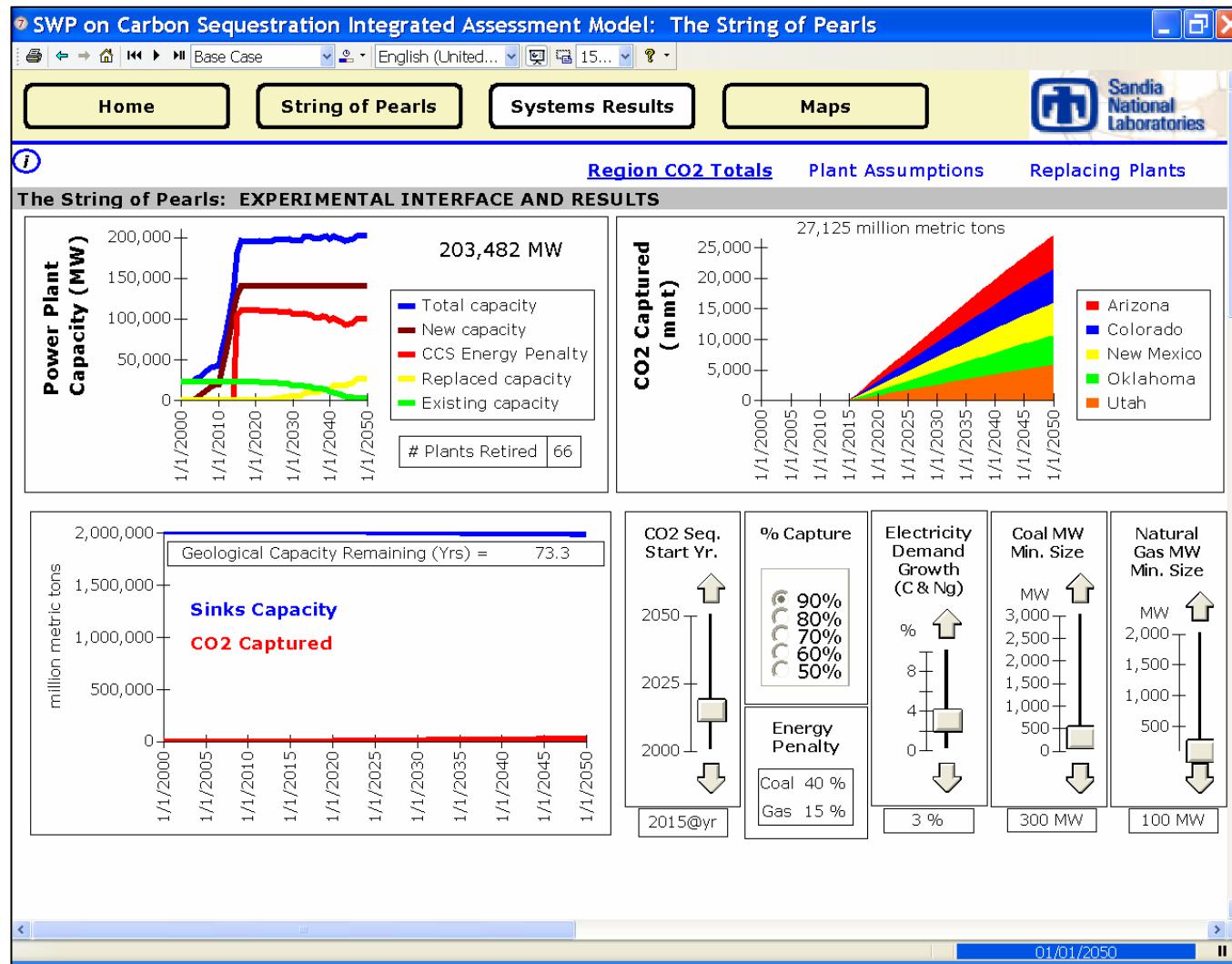
The String of Pearls: NM AZ CO NM OK UT Pipelines # selected 218 Go To Map

Justis-Blinebry-Tubb-Drinkard (48 mmt)	50	<input checked="" type="checkbox"/>	Blinebry Oil and Gas (Oil)-Blinebry (146)	65	<input checked="" type="checkbox"/>
Bagley North-Permo-Pennsylvanian (52)	51	<input checked="" type="checkbox"/>	Grayburg Jackson-Seven Rivers-Queen-Grayburg-San Andres (161)	66	<input checked="" type="checkbox"/>
Dagger Draw South-Upper Pennsylvanian (53)	52	<input checked="" type="checkbox"/>	Langlie-Mattix-Seven Rivers-Queen Grayberg (169)	67	<input checked="" type="checkbox"/>
Eunice North (Oil & Gas)-Blinebry-Tubb-Drinkard (63)	53	<input checked="" type="checkbox"/>	Indian Basin-Upper Pennsylvanian (Prorated Gas) (178)	68	<input checked="" type="checkbox"/>
Blanco-Pictured Cliffs (Gas) (63)	54	<input checked="" type="checkbox"/>	Empire-ABO (181)	69	<input checked="" type="checkbox"/>
Vacuum-Abo Reef (73)	55	<input checked="" type="checkbox"/>	Eumont-Yates-Seven Rivers-Queen (Gas) (185)	70	<input checked="" type="checkbox"/>
Vacuum-Glorieta (76)	56	<input checked="" type="checkbox"/>	Jalmat-Tansill-Yates-Seven Rivers (Gas) (187)	71	<input checked="" type="checkbox"/>
Crossroads-Siluro Devonian (79)	57	<input checked="" type="checkbox"/>	Jalmat-Tansill-Yates-Seven Rivers (Oil) (209)	72	<input checked="" type="checkbox"/>
Eumont-Yates-Seven Rivers-Queen (Oil) (83)	58	<input checked="" type="checkbox"/>	Vacuum-Grayburg-San Andres (413)	73	<input checked="" type="checkbox"/>
Indian Basin-Upper Pennsylvanian (Associated) (84)	59	<input checked="" type="checkbox"/>	Eunice Monument-Grayburg-San Andres (469)	74	<input checked="" type="checkbox"/>
Dagger Draw North-Upper Pennsylvanian (84)	60	<input checked="" type="checkbox"/>	Basin-Dakota (Prorated Gas) (484)	75	<input checked="" type="checkbox"/>
Denton-Devonian (90)	61	<input checked="" type="checkbox"/>	Hobbs-Grayburg-San Andres (533)	76	<input checked="" type="checkbox"/>
Drinkard-Drinkard (96)	62	<input checked="" type="checkbox"/>	Basin-Fruitland Coal (Gas) (739)	77	<input checked="" type="checkbox"/>
Blanco South-Pictured Cliffs (Prorated Gas) (113)	63	<input checked="" type="checkbox"/>	Blanco Mesaverde (Prorated Gas) (867)	78	<input checked="" type="checkbox"/>
Maljamar-Grayburg-San Andres (115)	64	<input checked="" type="checkbox"/>			

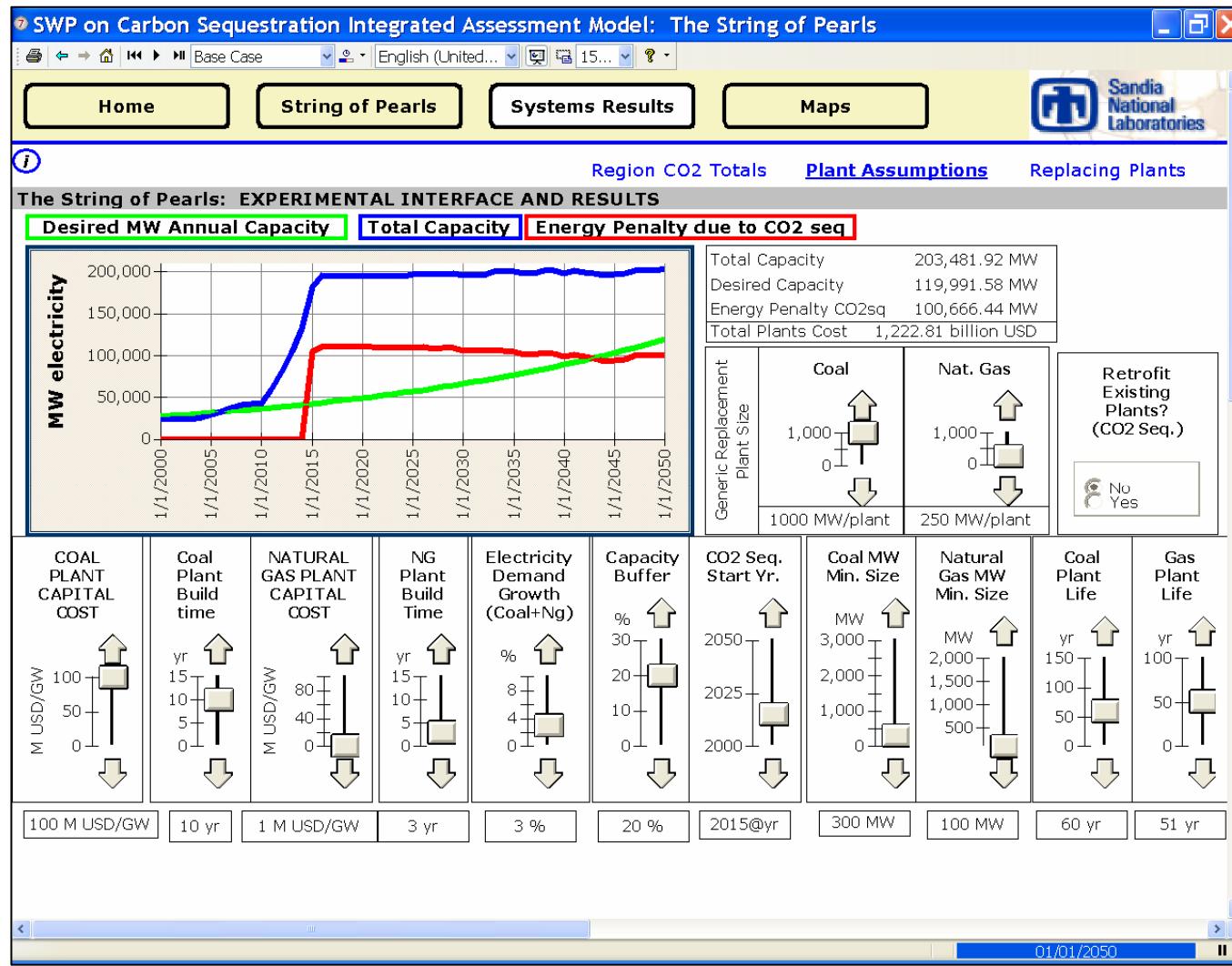
Sinks 42 - 49 Sinks 79 - 107

01/01/2050

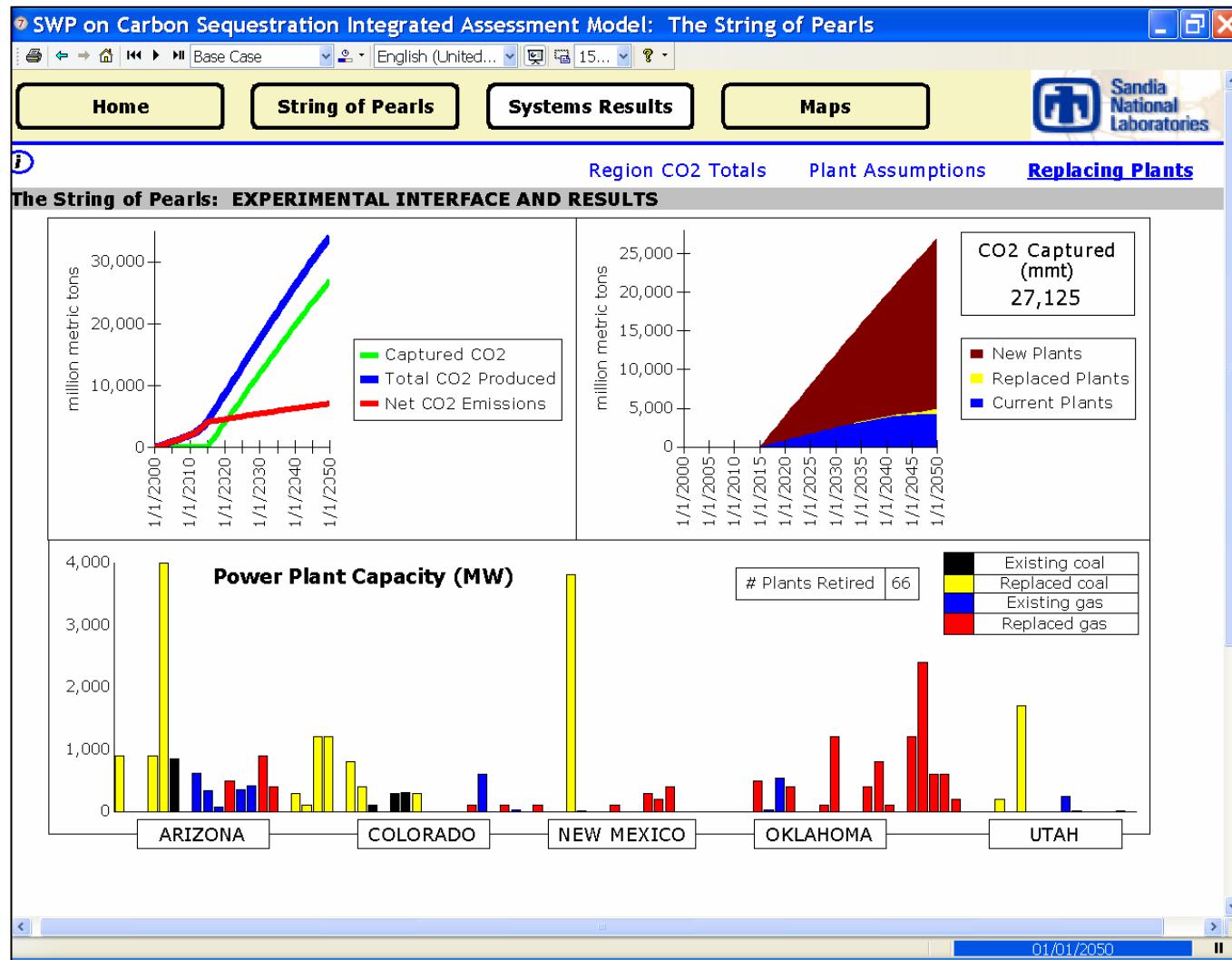
Appendix: The String of Pearls Model's Working Interface



Appendix: The String of Pearls Model's Working Interface



Appendix: The String of Pearls Model's Working Interface



Appendix: A Model Scenario, Selecting only Oil and Gas formations & those \geq 500 million metric tonnes

Results
for the
San Juan
Power
Plant
(1779
MW)

Select
only Oil &
Gas
Sinks
 \geq 500
mmt

SWP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Home String of Pearls Systems Results Maps Sandia National Laboratories

The String of Pearls: Choose a CO2 source (Coal, Gas, Custom), and watch or select the String of Pearls sinks.

Source: Select a Source

Use selected Source (e.g., San Juan)
 Use custom Source (e.g., Lat., Long.)

NM-SAN JUAN, COAL: 1779 MW (Default)

Sinks: Select from the database of Sinks

Arizona
 Colorado
 New Mexico
 Oklahoma
 Utah
 Coal Bed Methane
 Oil/Gas
 Saline Aquifer
 Pipelines

Maximum Distance from Source (km)

Minimum Capacity of Sink (mmtonnes)

Region CO2 Totals Plant Assumptions Other

Sink(s): Automatic String of Pearls, or Custom Sink Option

Electricity 9.70 cents per kWh Note: illustrative electricity cost only

Plant	Sink	Distance (km)	Cost (\$/tonne)
Selected	53	81.2	39

Power Plant

from Sink	to Sink	Distance (km)	Cost (\$/tonne)
53	52	30.5	37
52	37	123.2	57
37	126	747.2	80
126	146	102.9	39
146	68	521.7	63
0	0	0.0	?
0	0	0.0	?
0	0	0.0	?

Sinks

Note: The "0" for a Sink indicates the end of the string of pearls.

Click here to Select Specific Sinks

Click here to Show Regional Perspective

Only 6 sinks
are \geq 500
mmt in the
SW
Partnership's
Oil & Gas
database

500 mmt =
~ 60 years of
fill capacity
per sink for
the San Juan
Plant

Appendix: The Model's Specific Sinks Selection Page for the Southwest U.S.

Can Select Specific Sinks by State

SRP on Carbon Sequestration Integrated Assessment Model: The String of Pearls

Home String of Pearls Systems Results Maps

Sandia National Laboratories

The String of Pearls: NM

AZ CO NM OK UT Pipelines # selected 218 Go To Map

1. Leticia-Blinebry-Tubb-Drinkard (48 mmt)	50	<input checked="" type="checkbox"/>	Blinebry Oil and Gas (Oil)-Blinebry (146)	65	<input checked="" type="checkbox"/>
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Maljamar-Grayburg-San Andres (115)	64	<input checked="" type="checkbox"/>			

Sinks 42 - 49 Sinks 79 - 107

01/01/2000

Formations with a check mark next to them are included in the 'String of Pearls' algorithm

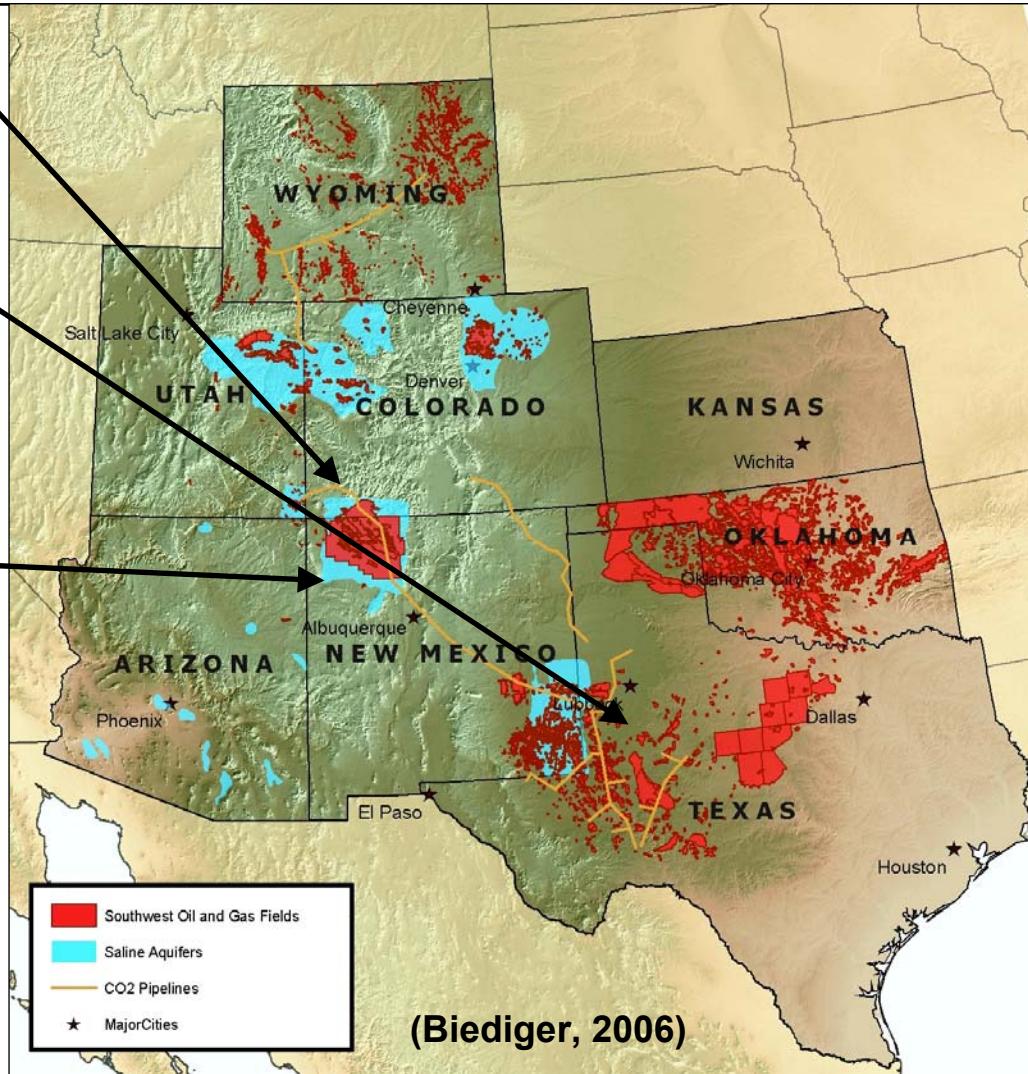


Appendix: Transportation & Storage, Infrastructure in the Southwestern US

CO₂ pipelines from CO to TX

Enhanced Oil Recovery (e.g., West Texas)

Potential Sequestration Opportunities in Oil Fields, Natural Gas Fields, and possibly Saline Formations



Working Totals for the Model

(most of the SW States as of January 2007, ongoing data collection)

Oil & Gas
 $\cong 17,000$ mmt CO₂

Saline Formations
 $\cong 2,000,000$ mmt CO₂

Appendix: Other Sandia Simulation Models, Assessing Costs and Energy Options

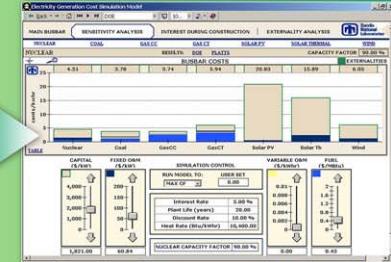
ECONOMIC DYNAMIC SIMULATION MODELS

STRATEGIC SUPPORT FOR HIGH-LEVEL PUBLIC POLICY DECISIONS AND SANDIA PROGRAMS

Understanding Technology Cost Options Electricity

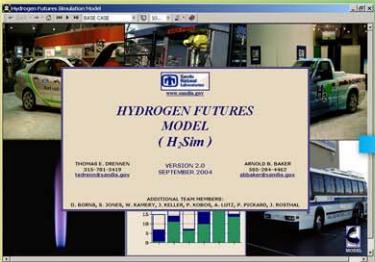


- Calculates electricity production costs for a variety of electricity generation technologies, including: pulverized coal, gas combustion turbine, gas combined cycle, nuclear, solar (PV and thermal), and wind

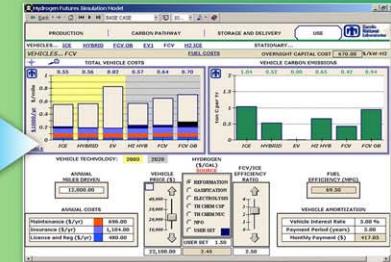


- Provides sensitivity analysis for key variables, including: capital, O&M, and fuel costs, interest rates, construction time, heat rates, capacity factors, and considers externality costs and pollution control options

Hydrogen



- Seeks to improve understanding of the economic viability and emission trade-offs of all stages of potential hydrogen pathways

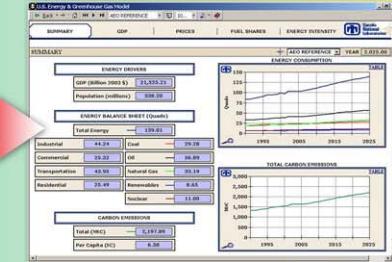


- Calculates the production, storage, delivery, and end use costs associated with a future hydrogen economy

Understanding Long Term Energy & Environmental Options U.S. Energy

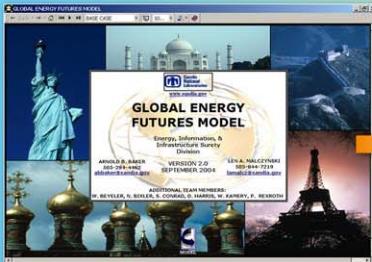


- Focuses on U.S. energy demand by economic and electric power sectors through 2025 to facilitate energy policy discussions

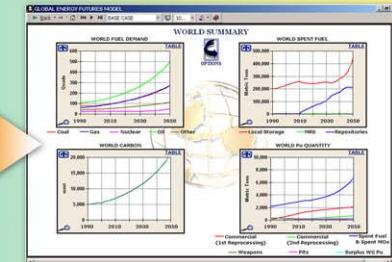


- Evaluates energy demand, carbon dioxide emissions, and oil import requirements, driven by gross domestic product, energy prices, energy intensities, and population effects

Global Energy



- Provides a global/regional perspective on trade-offs for economic growth, energy demand and environmental emissions to 2050, including the full nuclear fuel cycle and related materials



- Links oil, gas, coal, nuclear, and renewable energy to GDP growth, energy intensities, carbon emissions, and twelve other measures of environmental impact for five regions of the world