Understanding Carbon Sequestration: A Systems Analysis Tool

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ABSTRACT

A team of collaborators within the Southwest Regional Partnership (SWP) on Carbon Sequestration developed an interactive software tool to help facilitate discussions involving the science, engineering, economic and policy considerations for a carbon sequestration pilot project. This paper demonstrates the Integrated Assessment model, and highlights the 'String of Pearls' network algorithm used to develop a potential carbon dioxide (CO_2) transportation network in sequence with existing infrastructure and speaks to the use of system dynamics in a government setting.

The 'String of Pearls' model framework can assess geological sink choices according to their distance from the point source (e.g., power plants), relative size (to maintain a useful fill lifetime for a project under consideration), relative distance from existing CO_2 transportation infrastructure such as pipelines, and other salient project attributes. The results indicate that the cost to capture CO_2 at point sources is the largest component of the overall CO_2 capture, transportation and storage system's initial cost estimate. The 'String of Pearls' Integrated Assessment model can help planners assess these issues using an integrated, systems view when deciding where to develop future carbon sequestration pilot projects. The modeling process and the model itself are described in this analysis.

INTRODUCTION

Seven regional partnerships were developed by the U.S. Department of Energy throughout the United States to assess the geological, economic and infrastructure potential for a large-scale CO_2 sequestration network. The Southwest Regional Partnership (SWP) for carbon sequestration developed several thematic committees over the last few years to address many aspects of a CO_2 sequestration network in the Southwestern United States. One of the committees, The Integrated Assessment (IA) thematic committee, developed an interactive computer model that initially served as a central presentation tool for the SWP, then as a type of general cost and flow model, and now continues to develop as a systems view framework for ongoing data assessment to help visualize source and sink combinations in the SWP region.[i] Additionally, the modeling framework can be used at a high level to assess CO_2 flow, cost and additional attributes for the potential carbon sequestration pilot projects in the region.

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The original proposal for the Integrated Assessment approach by the SWP presented a causal loop diagram and a brief description of the system dynamics approach that would form the backbone of the integrated assessment work. The original goals of the original modeling effort were to produce an application that would be used for: 1) scenario development where policy makers and regulators explore a range of "what if" scenarios, 2) constituency development wherein industry representatives and other partners can examine the scenario results as a test of their viability and ability to be implemented, and 3) outreach and education where the model would be shown directly to the public and used as an aid to improve their understanding of CO_2/energy cycle issues and complexity, explain the decision process, and be directly engaged in evaluating proposed sequestration options.

The primary deliverable was a publicly-accessible (through workshops), integrated assessment model for application in mediated group modeling. That desire has been met by interaction with the Partnership via face-to-face and web-enabled meetings plus explicit desires from the DOE sponsors to include other features in the model.

Since the beginning of the project (April 2003) the modeling efforts have evolved in response to input from the 44 organizations that are members of the SWP. The timeline below gives a high-level view of the IA progress.

Fiscal Year	Task
2004	Developed a 'Test Case' model with a limited set of New Mexico sources and sinks including rudimentary distance calculations
2005	Developed the initial minimal spanning tree algorithm, 'String of Pearls'
2006	Developed a full Southwest regional model of sources and sinks
2007	Developed a source power plant aging chain and replacement module

THE INTEGRATED ASSESSMENT MODEL: AN OVERVIEW

The Integrated Assessment model is a dynamic simulation computer model used by the Southwest Regional Partnership on Carbon Sequestration to assess power plant (CO_2 source) and largely geological structure (CO_2 sink) combinations at a high level. The model is a tool that

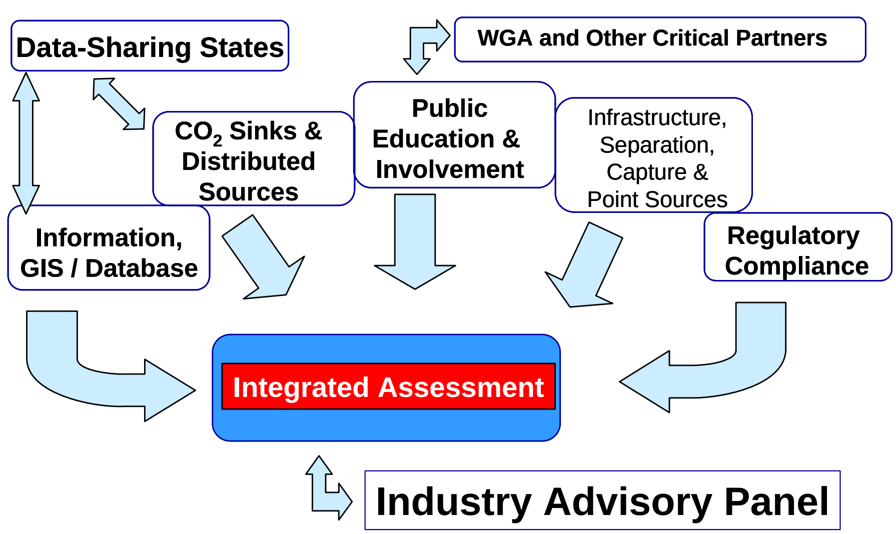

Figure 1. Thematic Committees & Partner Integration (adapted from McPherson, 2005a).

highlights the relative amount of CO_2 a sequestration project captures at a power plant, calculates the pipeline capacity required for the project to transport the CO_2 to a sink, and addresses the time scales involved (e.g., how many years will it take until a sink is filled with CO_2 from a power plant of a certain type) along with the salient economics. Figure 1 illustrates the SWP's general structure, and highlights the Integrated Assessment's role within the project's overall scope.

The Integrated Assessment Team largely served as a committee, in the first phase of the project, to help present the information generated from the select thematic committees (e.g., CO_2 sources, sink characterization and economic assessments) in a generic framework. Figure 2 illustrates the underlying framework of the Integrated Assessment model.

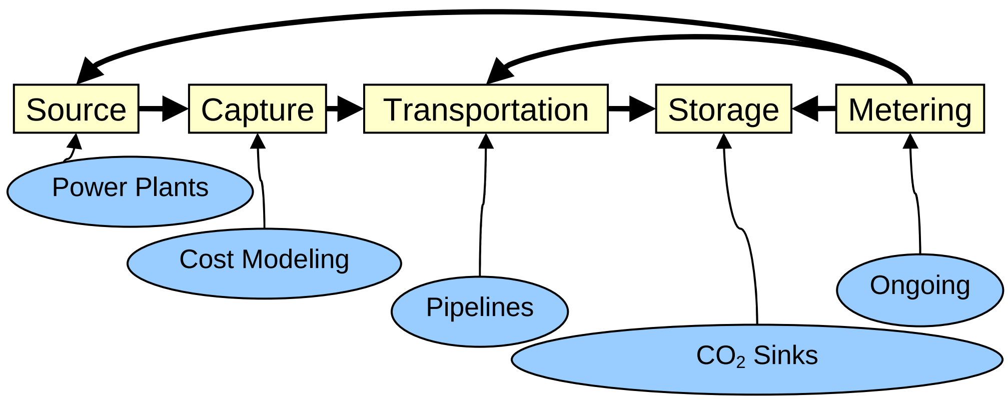

Figure 2. The Integrated Assessment model's underlying CO_2 flow and cost model structure.

The Integrated Assessment team used the model on an initial test case in New Mexico, then moved on to the entire state of New Mexico, and finally expanded the model to include the entire southwestern region of the U.S. This 'bottom up' modeling approach allows the SWP to continuously improve the model in a transparent and consistent way.[ii]

The initial test case model calculated all of the illustrative cost and CO_2 flow combinations between four power plants in New Mexico, and seven geological sequestration sites, and ranked the cost combinations from lowest to highest.

The original test case's CO_2 separation and capture calculations were based directly on the Integrated Environmental Control Model (IECM) (CMU, 2004).[iii] The model also employs the CO_2 emissions data for power plants from the 2002 version of the Emissions and Generation Resources Integrated Database (eGRID) (EPA, 2005). The CO_2 transport and injection equations for CO_2 storage calculations are based on Ogden (2002), Williams (2002) and industry participation by Mike Hirl (Hirl, 2004).[iv] The CO_2 sinks database was developed by the sinks committee of the SWP, and managed by the Utah AGRC.[v] Additional data on power plants was obtained from the Electricity Supply and Demand Database and Software (NERC, 2006).

Figure 3 illustrates a summary screen from the original test case model developed in 2004 and early 2005.

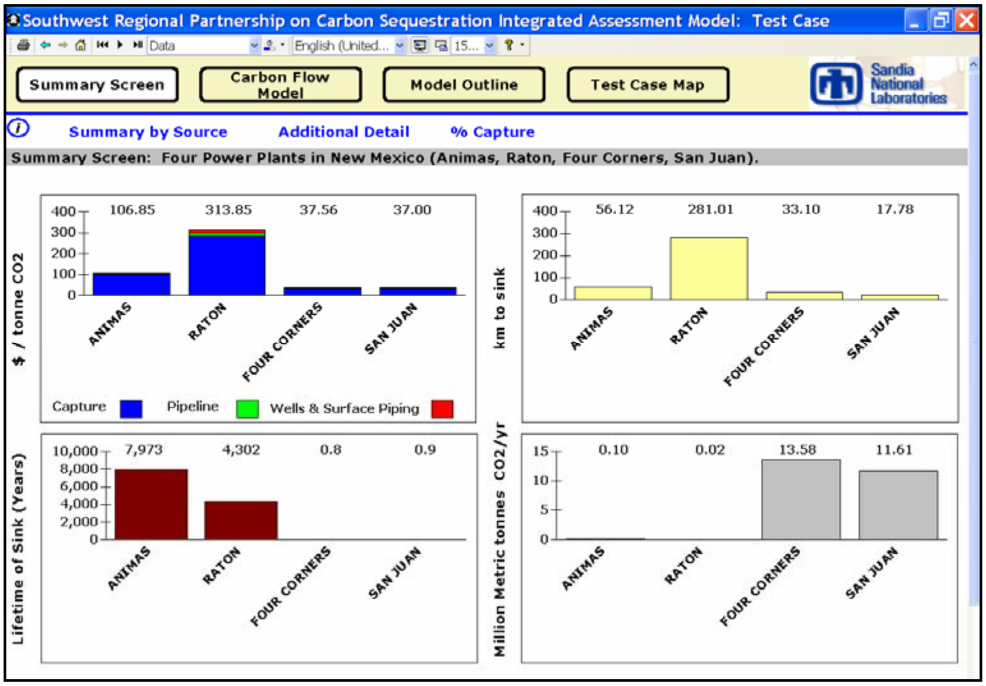

Figure 3. The initial Integrated Assessment Model framework applied to a test case set of power plants and sinks (four power plants, seven geological sinks, fill lifetime and distance to the nearest geological sink; model version as of Summer 2005).

THE INTEGRATED ASSESSMENT 'STRING OF PEARLS' PIPELINE NETWORK MODEL: INTERFACE DEVELOPMENT AND USER OPTIONS

The Integrated Assessment team expanded the initial test case version of the model to include the whole state of New Mexico, and then the full southwestern region of the United States. The full New Mexico model was the first version to employ the innovative 'String of Pearls' model module (Kobos et al., 2006). The 'String of Pearls' is a metaphor for the string of new or existing pipelines connecting a collection of potential CO_2 sources and sinks. The 'String of Pearls' module calculates the transportation distances, based on a great circle distance algorithm, for CO_2 from the source of the CO_2 (e.g., power plant) to the closest sink (e.g., geological reservoir) (Stephens, 1998). The 'String of Pearls' module, therefore, builds on hypothetical pilot project pipelines and potential cost-saving connections with existing CO_2 pipeline infrastructure in the southwestern United States. Figure 4 illustrates a map of the New Mexico CO_2 sources and sinks considered in the initial New Mexico-specific 'String of Pearls' prototype model.

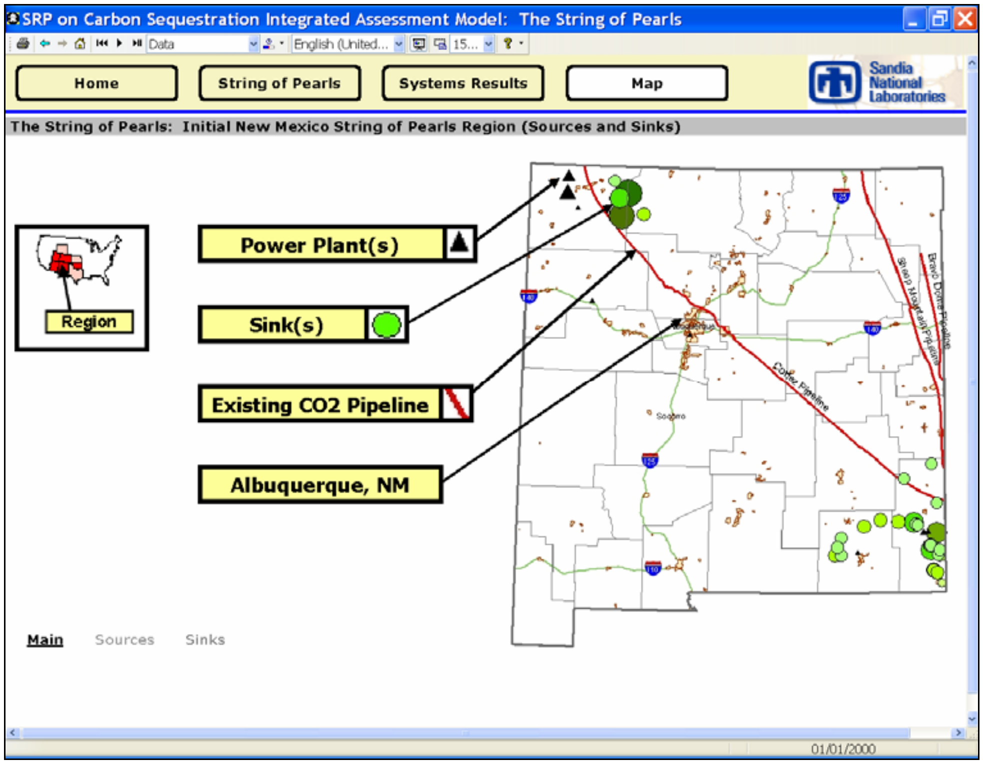

Figure 4. Map of the CO_2 sources (power plants) and geological sinks considered in the New Mexico prototype Integrated Assessment 'String of Pearls' model.

The CO_2 sinks are assigned their place in the 'String of Pearls' so that as one fills to capacity, the pipeline network extends to the next viable sink, fills it, and so on until the model develops a hypothetical pipeline network system. This allocation mechanism concept is also generally known as a minimal spanning tree approach. All of the links between various combinations of the selected sources and various sinks are the potential pipeline routes. This technique serves as a linear proxy for pipeline routes, and lays the groundwork for future, additional analysis throughout both the Southwestern Regional Partnership area in the United States and beyond. With this technique, the model addresses additional metrics (e.g., largest sink volume, acceptable distance between sinks, etc.) for systems insight. Figure 5 illustrates a hypothetical illustration of a pipeline route within the Integrated Assessment model.

The full 'String of Pearls' model developed in the summer of 2006 builds on the framework of the original test case model, and the full NM model developed in Phase I of the Southwest Regional Partnership on Carbon Sequestration. The full 'String of Pearls' version of the Integrated Assessment model includes 218 geological sinks (plus an additional 107 points along existing CO_2 pipelines), and 83 power plants across five states. The full 'String of Pearls' model can determine the source to sink distances and associated economics (various components remain to be refined, potentially across all of the regional partnerships in the U.S.) for any of the source sink combinations between the power plants, geological sinks and select pipeline nodes. The model can illustrate up to the top ten closest sinks to any of the ten power plants, but calculates all of the possible combinations. Additionally, the model includes high-level measurement, monitoring and verification (MMV) costs based on Benson et al. (2004) of approximately \$0.16 to \$0.31 per tonne of CO_2 to begin assessing how these costs will affect the economics of the overall sequestration systems.

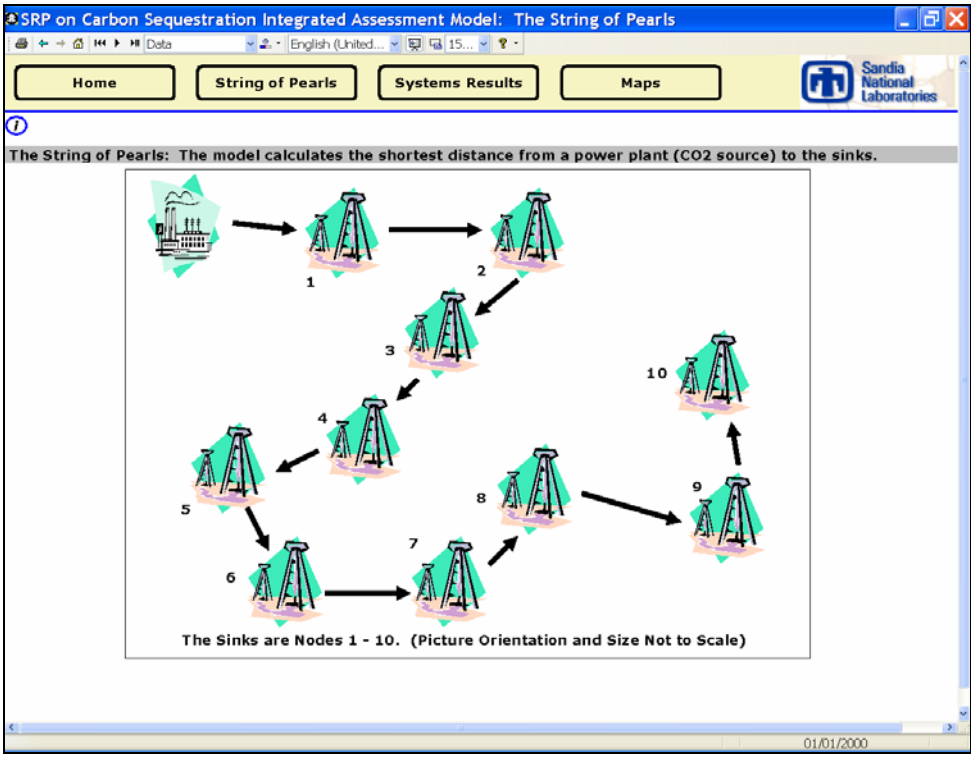

Figure 5. Illustrative 'String of Pearls' network allocating CO_2 between sinks from a point source based on a least distance solution.

The cost metrics are based on previous work using the IECM model results and a regression equation proxy for the cost to capture CO_2, or, the model allows the user to enter their own cost metrics for complete analytical flexibility.[vi] Additionally, the carbon capture community is looking to reduce the uncertainty regarding overall carbon capture systems' cost and performance parameters. The cost to capture carbon dioxide using an amine (MEA)-based system holds substantial potential to reduce the cost to half or less of their current costs according to recent work (Rao and Rubin, 2002; Rao et al., *in press*). The Integrated Assessment model will continue to include technology developments as they develop.

Ultimately, one of the central innovations of the 'String of Pearls' model is the ability to include existing CO_2 pipeline infrastructure in addition to the specific class of geological sinks (e.g., oil/gas, coal bed methane, saline aquifers) in the network algorithm. The model includes portions of the Bravo Dome, Cortez, and Sheep Mountain pipelines to allow for 'piggybacking' into current CO_2 pipelines across the southwest region included in the model. The model considers these pipelines as 'virtual sinks' in that when a CO_2 source is closer to a pipeline node than a geological sink, the model will connect the source's output to the trunk pipeline. This gives planners the ability to begin considering the pipeline as a sink because of its established CO_2 pipeline transportation right-of-way designation, security in the known operations history of the pipeline, and the ability to move CO_2 between basins.

Figures 6 illustrates the main 'System Results' front page the model user can interact with. It shows the top 10 closest single source to multiple sink string of pearls cost results broken down by components (upper left hand corner; stacked capture, pipeline, wells and MMV costs), the years each sink will last along the hypothetical pipeline network (upper right hand side), the percentage capture assumptions and corresponding capture costs (regression analysis based, or custom capture percent, and custom cost sliders), pipeline and well cost multipliers (to illustrate the relative cost contribution of these components to the overall system if they change given new information), and finally the MMV costs within a slider to allow for a cost sensitivity analysis.

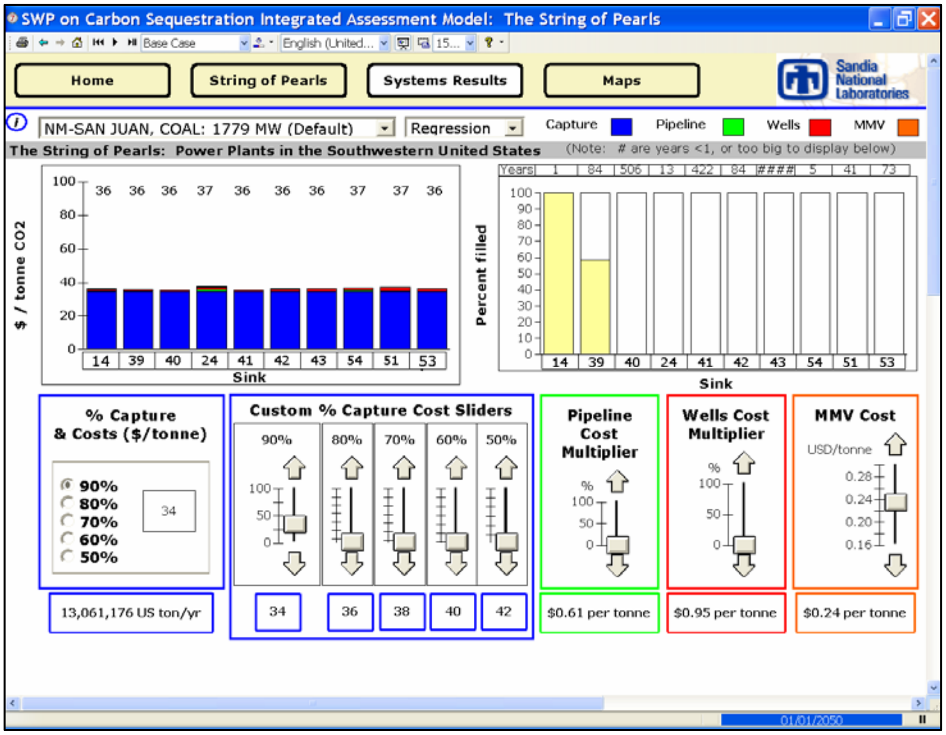

Figure 6. The Systems Results for the San Juan Power Plant CO_2 Source to Multiple Geological Sinks using the full 'String of Pearls' Pipeline Network Algorithm. (Note: The screenshot illustrates the stacked systems costs (upper left), and the years of useful sink fill time (upper right)).

The model user can query the sinks database based on the geonode (center) of the sink (e.g., which state is the center of the basin in), the type of sink (e.g., coal bed methane, oil/gas, saline aquifer), the maximum distance the source can be from the sinks for the 'String of Pearls' algorithm to consider it (e.g., to minimize the distance of the pipeline network to be developed), and the minimum capacity of the sinks (e.g., at least a certain amount of million metric tonnes of CO_2 to maintain a useful sink lifetime for a project on the scale of an existing power plant). The specific sinks per state can also be selected in the custom sinks page, which also serves as the legend for the sink names according to their assigned sink number. For example, figure 6 shows sink number 14 as the first to meet the selection criteria, which is the Barker Dome-Hermosa Group (oil/gas) formation with 10 million metric tonnes of CO_2 storage capacity. The second sink selected after the Barker Dome-Hermosa Group was the San Juan and Paradox Basin 1-Miss Leadville Limest (saline aquifer) formation with 1,000 million metric tonnes of capacity. Figure 7 illustrates the same San Juan power plant as a hypothetical source of CO_2, but includes only the oil and gas reservoirs in the String of Pearls algorithm for the entire SWP region to demonstrate how the pipeline network results adjust to the new constraint.

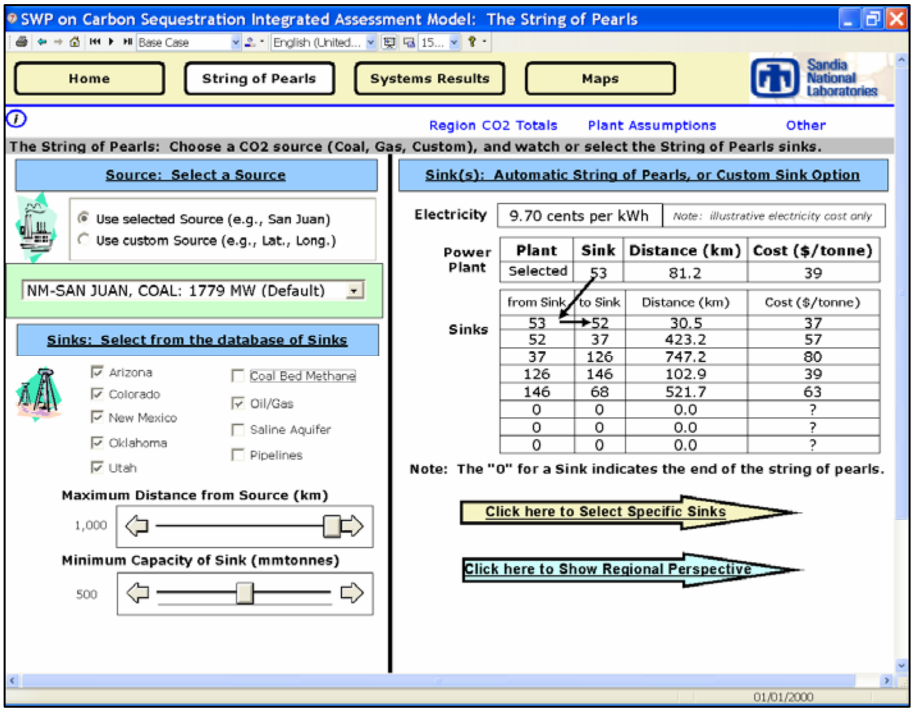

Figure 7. The Full 'String of Pearls' model that only considers oil and gas formations as geological sinks in the SWP region, and those that are of at least 500 million metric tonnes in size (Note: this approximates to 60+ years' worth of capacity from the San Juan Power Plan).

The user can also select a 'custom' location for a power plant by specifying the coordinates (latitude and longitude) of the power plant. The model user can illustrate, using the String of Pearls model, where to potentially cite a new power plant when considering existing carbon sequestration infrastructure and available geological sinks.

Lastly, the model user has the ability to select specific geological sinks throughout the SWP region. This allows the model user to assess a specific power plant's CO_2 and cost profile relative to a specific geological sink to determine the high-level metrics a pilot project might entail (e.g., how much would the capture, transportation and storage cost, how long might the pipeline have to be, how large is the sink relative to the plant's CO_2 output).

THE FULL SOUTHWEST REGIONAL PARNTERHIP STRING OF PEARLS MODEL: PUTTING THE SCALE OF THE SOURCES AND SINKS INTO CONTEXT

The strength of the Integrated Assessment Model's framework is its ability to include additional CO_2 sources, sinks, and modeling options as the SWP expands its scope. The changes range from data with a higher degree of granularity to potentially data from other regions of the U.S. Figure 8 illustrates the total CO_2 sources (emissions from power plants) in the state of New Mexico, the main states within in the SWP, and the whole of the United States. The model also includes a power plant construction cycle based primarily on the work of Ford (2001). The model includes changes in plant capacity due to the parasitic loss due to carbon capture when retrofitting existing plants and a capacity factor for growth factor in electricity demand. The anticipation of that capacity gap, construction and licensing time delays, result in some oscillatory behavior for building capacity in the coming decades.

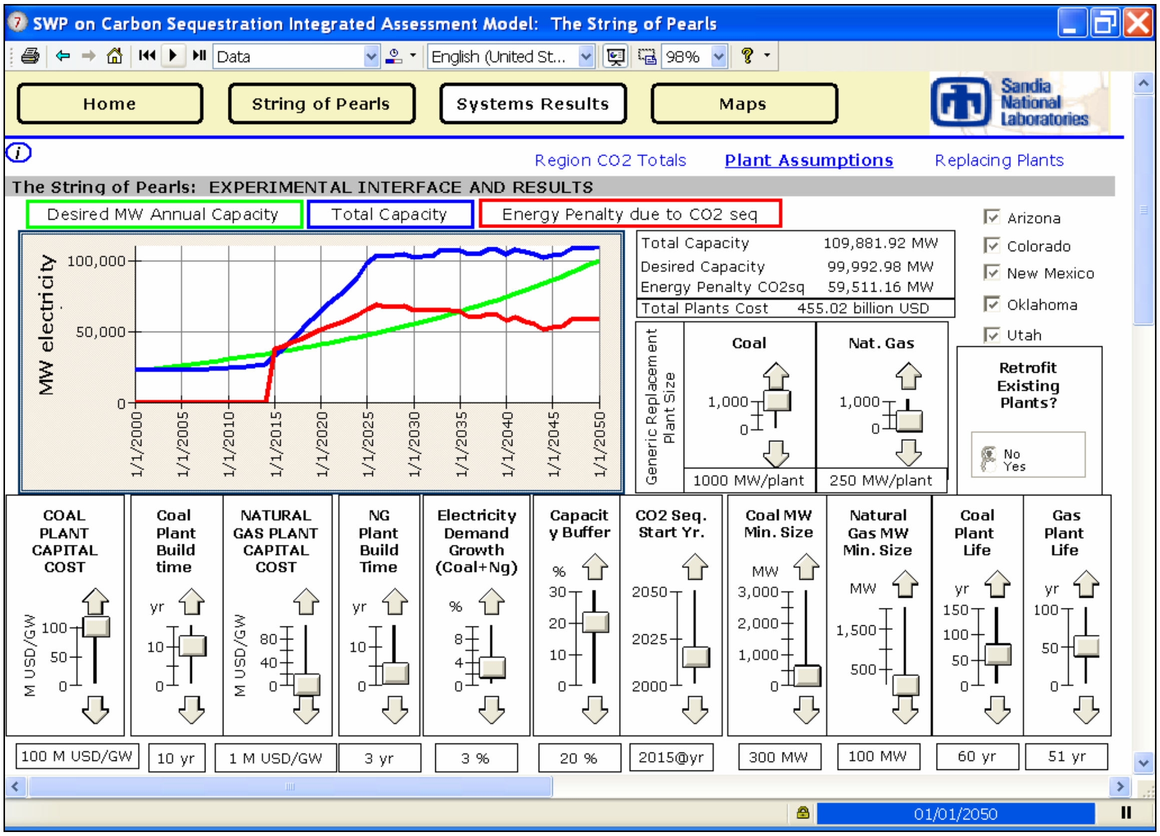

Figure 8. The working interface presenting electricity generation capacity due to carbon capture penalty and new capacity growth in the U.S. to 2050.

Figure 9 shows a summary screen that demonstrates the replacement of existing utility coal and gas plants over time. Given a modest 3% increase in MWh demand per year the working results indicate the majority of existing plants will be replaced by the year 2050. When total projected demand exceeds the power generated from existing plants and their replacement plants, the model builds new capacity. This replacement cycle provides an opportunity to build more efficient plants that are carbon capture ready. For perspective, the SW. region includes a very small proportion of the nation's CO_2 emissions (Figure 10).

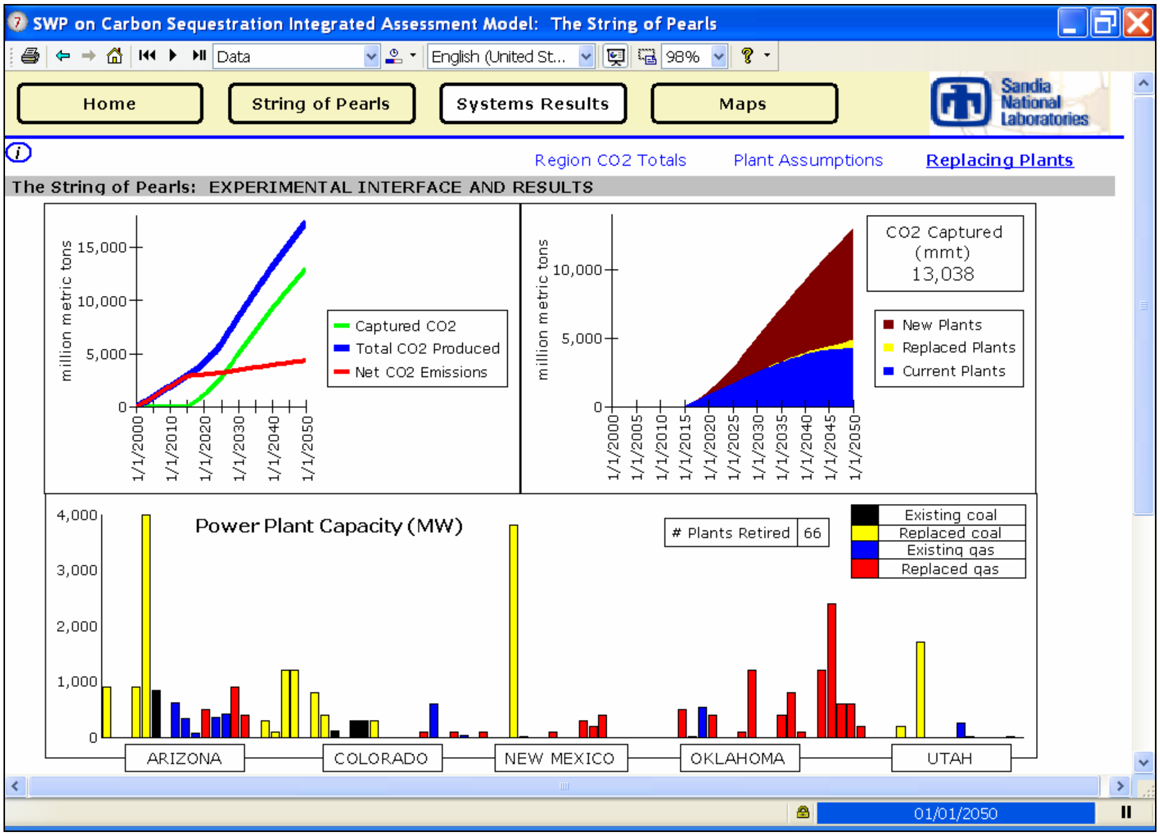

Figure 9. The 'Replacing Plants' interface. This snapshot was taken at the end of model run (the year 2050). The lower bar graph shows that almost the entire fleet of the utilities' coal and gas powered electricity generating capacity will be replaced by 2050.

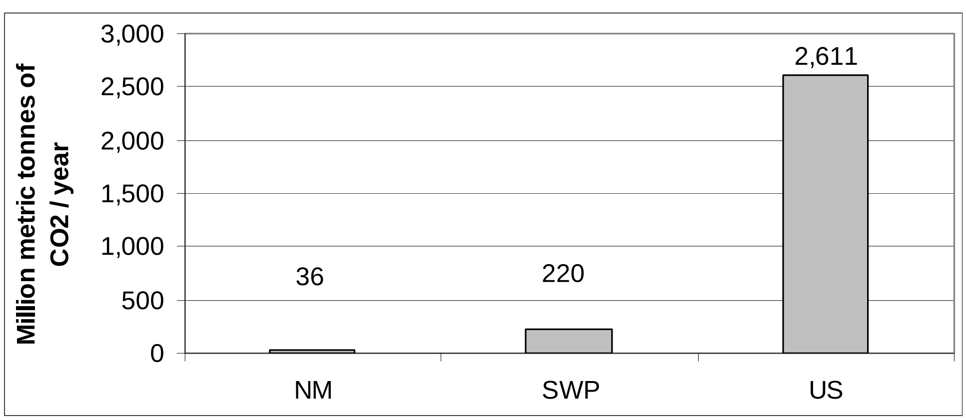

Figure 10. Carbon Dioxide Emissions in 2000 for the State of New Mexico, the Southwest Regional Partnership (SWP) states, and the United States (Note: These results only include stationary power plants in this version of the model, and the 'SWP' is the sum of the emissions from Arizona, Colorado, New Mexico, Oklahoma and Utah, (EPA, 2005)).

Exports of electricity across state lines will likely raise policy challenges when assessing where and how electricity producers and users will pay for CO_2 sequestration technologies. For additional context, Arizona, Colorado, New Mexico, Oklahoma and Utah, for example, export roughly 63, 11, 73, 32 and 65 percent of their electricity (EIA, 2004) to regions beyond their state's boundaries, respectively.[vii] Figures 11 and 12 illustrate the installed megawatts and the associated CO_2 emissions within the selected Southwestern states.

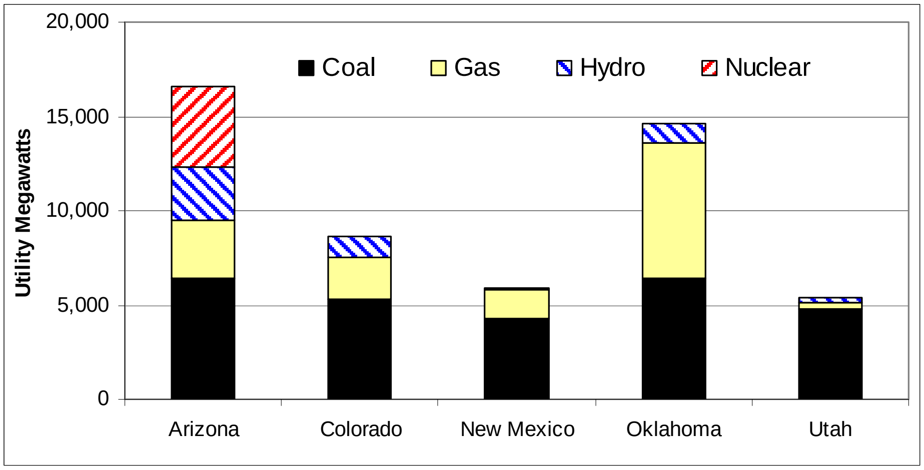

Figure 11. Utility-based Installed Megawatts for States in the Southwest U.S. in 2000 (Note: Oil-based and other fuels represented 2% or less of the total installed megawatts) (EPA, 2005).

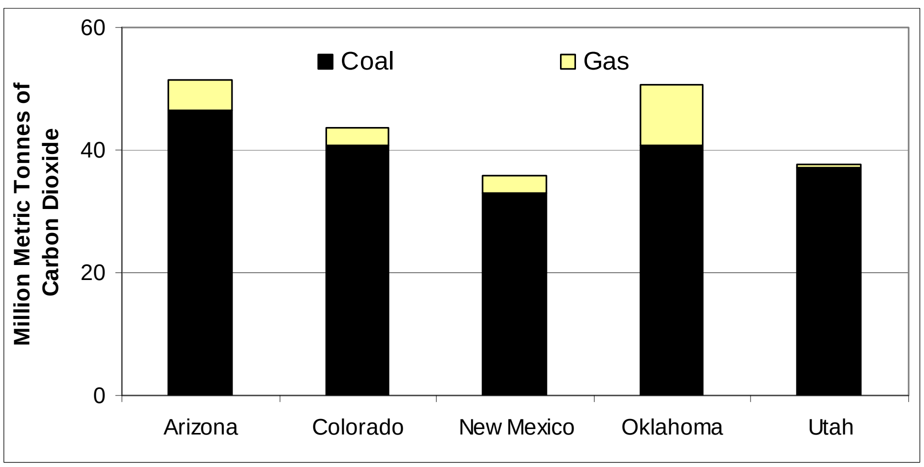

Figure 12. Million Tonnes of Carbon Dioxide Emissions from Utilities for States in the Southwest U.S. in 2000 (Note: Oil-based and other fuels represented 2% or less of the total CO_2 emissions. EPA, 2005).

The sources database will likely continue to develop as more (or less) sources are considered for the Integrated Assessment model. The sinks database will also continue to develop as more (or less) data is considered for the overall regional assessment. Figure 13 illustrates the geological sinks data in the full 'String of Pearls' version of the Integrated Assessment.

The SWP continues to collect CO_2 sinks data for Texas, other states, and potentially other pilot projects as the overall SWP looks to address several key issues such as what types of sinks should or should not be included in the analysis (e.g., those of a certain size, location, depth, within certain regulatory constraints, etc.).

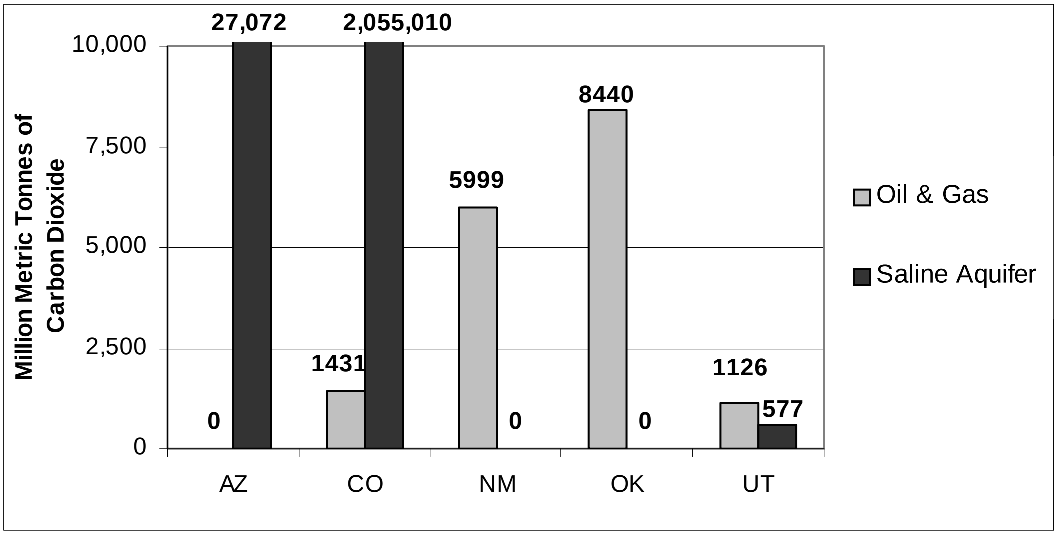

Figure 13. Million Metric Tonnes of Potential Carbon Dioxide Storage Capacity in the SWP (Note: Coal Bed Methane capacity in UT is 57 million metric tonnes in the working database employed by the full String of Pearls model as of July 2006; capacities shown are those developed by the thematic committees (Biediger, 2006)).

MODELING SOFTWARE ISSUES

System dynamics models exhibit five broad components or classes of features.[viii] The 'String of Pearls' (SOP) application focuses primarily on uncertainty analysis, forecasting and optimization. The primary reason for this derives from the set of stakeholders in the SWP. Although system dynamics modeling does not immediately imply the construction of a computer based model[ix], the demands of stakeholders driven by their accumulated experience with modeling and simulation, the capabilities of the modeling software and the need to mimic or duplicate other less systemic but detailed software models demands that system dynamics applications include increasingly non-system dynamics features. Over time, as the model became increasingly intricate, the corresponding application (model plus interface) in turn became increasingly more intricate. In the author's experience, many of our stakeholders have little experience with system dynamics and think of the models, made operational in software, as simply computer applications. In the purest methodological sense, the SOP is not only a system dynamics application but a hybrid of system dynamics, geographic information systems, and operations research.

The authors continually made decisions about what and how to include model features into the application that fall outside the system dynamics framework. The goal of these decisions, of course, was to have a useful and meaningful application. Fortunately or not, depending upon one's perspective, system dynamics modeling software now includes the ability to include other modeling and simulation paradigms. The team employed Powersim Studio 2005[x] to build the SOP application. Studio 2005 has the standard system dynamics methodological tools, an interface capability, and the above mentioned ability to include other modeling paradigms. We made use of the VBFUNCTION() tool that permits a modeler to build their own functions if expressed in Visual Basic Script (VBScript). VBScript is intrinsic to the

Microsoft Windows environment and therefore comes with all Windows operating systems. The VBFUNCTION() has served a number of roles in the SOP application including:

(1) Data manipulation,
(2) Iteration to close a gap,
(3) General purpose algorithm development.

The SOP model includes a substantial amount of externally accessed data in the form of Microsoft Excel files. Much of this data is easier to organize outside of Studio and then be manipulated in Studio for the purposes of interface development, data aggregation, or relationship calculation(s). VBScript provides a simple solution to these challenges. Studio, like most system dynamics software, has a large set of built in functions. It is not, however, a general purpose programming language. The algorithm we employ to estimate the great circle distance between sources and sinks must iterate to an approximate solution. This could be done within the traditional stock and flow paradigm, but with time units and time steps that do not match the overall model. This capability was also added via employing the VBScript. Finally, the minimal spanning tree algorithm was obtained in the form of pseudo-code from the research community. It was then constructed in VBScript to employ it within the Studio environment.

One must be cautious about opening models to other modeling paradigms via VBScript. There is a tendency when posed with a modeling problem to simply default to a VBScript solution; all the more so when modelers have experience in software engineering and programming. This could be a troublesome approach. Even though more and more system dynamics applications have become hybrid applications, a careful examination of the system dynamics nature of the problem should be undertaken before choosing VBScript as 'the way out' of challenging modeling problems.

The power of system dynamics software is steadily increasing. This makes the modeler's task easier and permits the use of new non-system dynamics features. One hope is that modelers produce useful applications that benefit from the underlying power of the system dynamics methodology with prudent complements of other methodologies.

DISCUSSION

Overall, the original goals as set for in the proposal submitted to the Department of Energy have been met, and there has been substantial evolution in the model's scope. The two reasons for this are: 1) shifting requirements over time from partnership members, and 2) complex data needs. The modeling effort here goes beyond the typical system dynamics model. Detailed information on power plants, geology, and technology are required to make the model interesting and useful to many of the 44 organizations participating in the SWP. The resulting integrated assessment model has both continuous and discrete elements and an assortment of algorithms that support the model but are not necessarily traditional to system dynamics. The modeling efforts during Phase I (2004 – 2005) focused mainly on oil and gas reservoirs within the state of New Mexico, and parts of the southwestern United States. The central insight gained from these initial efforts is the cost to capture carbon dioxide at the point sources represents the majority of the overall system's costs. Thus, in a carbon constrained world, carbon sequestration projects might focus their efforts on new, cost effective technology to capture carbon dioxide and a corresponding series of sinks with sufficient capacity to provide a useful sink lifetime for the project.

Phase II (2006 and beyond) efforts have included even more detailed, region-wide source-sink matching and select pilot projects. Additionally, the model includes a power plant aging and replacement cycle that accounts for the parasitic power losses which may occur in the face of wide-scale adoption of carbon capture and sequestration technologies to the existing energy infrastructure.

As more information becomes available throughout the SWP, the Integrated Assessment model will likely include this information to improve not only the scope of the problem domain it can assess, but also the granularity of the cost, geological and monitoring information it encompasses. Potential additions and modeling capabilities may include developing time-to-build constraints for the infrastructure, developing a capital budgeting-oriented sub-framework (e.g., if given a limited budget, which project might develop), and looking to determine how the regulatory environment might drive (or constrain) the wider adoption of carbon sequestration technologies.

Construction of the ‘String of Pearls’ model and interface posed some challenges. This may have been due, in part, to unfamiliarity with system dynamics and the related modeling tools across parts of the SW Partnership, and an expectation that the software interfaces would be more custom (partner) specific instead of a more usable, general approach. Using the more general approach has proved to be extremely useful when demonstrating the model to both a general, and more specialized audience including to members of other regional partnerships.

With the full ‘String of Pearls’ Integrated Assessment model, planners can assess the technologies, economics and associated issues using an integrated, high-level systems view when deciding where to develop future carbon sequestration projects and to understand the overall potential carbon sequestration future in the U.S.

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[i] This paper builds on the work of Paananen (2004), Kobos et al., (2005a, 2005b), and Kobos et al., 2006.

[ii] The New Mexico Bureau of Mines, the Colorado Geological Survey, and Los Alamos National Laboratories helped characterize the geological sinks according to their size, depth, and other associated attributes.

[iii] The Gas Technology Institute (GTI) used the IECM to calculate the CO_2 capture costs for several power plants as part of their Phase I participation in the SWP.

[iv] Based on the Ogden (2002) model of CO_2 disposal costs for CO_2 sequestration, Williams (2002) develops the general framework where the cost of CO_2 disposal is a function of the cost of the pipeline transmission (CPT) + the cost of disposal wells (CDW) + the cost of surface piping near the disposal wells (CSP); where CPT($/t$CO_2$) = CPT_0*($Quantity_n$/$Quantity_0$)^-0.53 * (length of $pipeline_n$/length of $pipeline_0$)1.24; Cost per well ($/well)=$1.0 million + ($1.25 million/km)*[depth(km)]; CSP=0.138*(Quantity-104.17)^0.253. The calculations developed for the IA also draw on the work of Drennen et al. (2004) and the work of Kobos et al. (2005a, 2005b).

[v] Barry Biediger of the Utah AGRC has been instrumental in the SWP by maintaining and managing the core SWP sinks data. The majority of the sinks database has been utilized in the Integrated Assessment model unless missing data prevented further analysis (e.g., sink's depth from the surface) or size constraints limited their usefulness (those less than 10 million metric tonnes in size, which equates to approximately one year's worth of storage (or less) for a large coal-fired power plant).

[vi] The Integrated Assessment Model began using direct results from the IECM model based on GTI work for hire (Meyer, 2006). For the full String of Pearls, the partnership is looking to characterize dozens of power plants and employs working regression equations based on these estimates to develop a cost-assessment framework. All costs listed in this paper should be considered preliminary, illustrative estimates. The regional partnerships throughout the country may adopt a standardized cost-assessment formula and/or methodology. Using this regression analysis allows the 'String of Pearls' model to develop in concert with these potential standardized assessments. As of the summer of 2006, the model employs the following working regression equations for coal and natural gas-fired power plants, respectively; Capture cost (coal plant) = 48.9683 + (0.0003 * Power plant MW) + (-0.2030 *% CO_2 captured); Capture cost (natural gas plant) = 117.6814 + (0.0409* Power plant MW) + (-0.6665* % CO_2 captured); R^2=0.9553 and 0.9574, respectively . Additionally, the model allows users to specify custom capture costs when more detailed information is available.

[vii] Colorado imported approximately 4% of its electricity in 2000 (EIA, 2005).

[viii] Zagonel and Corbet 2006.

[ix] Sterman 2000.

[x] Powersim Corporation, www.powersim.com