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A Risk-Based System Analysis Framework for Geological Carbon Sequestration

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Abstract

The purpose of this project was to characterize existing carbon capture and sequestration technologies at a high level, develop an analytical framework to help assess the technologies, and implement the framework in a system dynamics model. The first year of this project succeeded in characterizing existing technologies to help focus the analysis on power plants. The assessment also helped determine which technologies are largely accepted by the carbon capture research community as relatively proven technologies, discuss the salient performance metrics, and assess the associated economics. With this information, an analytical framework was developed to assess the technologies from a systems view perspective. With this framework, the Carbon Sequestration and Risk Model (CSR) was developed to assess performance and economic risk issues as they relate to global atmospheric CO_2 concentration goals and single plant scale projects to characterize the economics of these systems.

ACKNOWLEDGMENTS

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PREFACE

The objective of this project in the first year was to characterize clean coal-based electric power production facilities and carbon sequestration technologies that either are currently available, or may be available within the next five to ten years. The report titled, "Carbon Sequestration and Clean Coal Technologies: Characterizing Systems and Evaluating Costs" was developed in the first year of this Laboratory Directed Research and Development (LDRD) project to address these issues under the guidance of Orman Paananen (Principal Investigator) and David Borns (Manager) (Borns et al., 2005). The full title of the two-year LDRD project was, "System Analysis of Carbon Sequestration with Clean Coal Technology." The technologies are considered at a relatively high level to provide a basis for developing correspondingly high-level models. The models would then be able to examine sequestration and cost tradeoffs between different combinations of clean coal electric power production and sequestration processes.

In the second and final year of this project, the goals were to (1) Characterize 'Clean Coal' and Carbon Sequestration Technologies (e.g., performance goals, economics, and the policy implications and considerations), (2) develop a research network for Sandia National Laboratories in the carbon sequestration community and collaborate between projects and within the community, (3) design and build a systems analysis framework and implement the framework in a systems model with the guidance of Peter Kobos (Principal Investigator for the second year of the project). The central theme of these three items is to address performance and economic risks within carbon sequestration systems. With this information, future energy systems models and analyses will benefit by looking to target research and development (R&D) funds to reduce performance uncertainty, and consequently economic uncertainty when looking to develop and potentially deploy carbon capture and sequestration technologies at scales beyond that of pilot projects. This is the summary report for the two-year project.

1. INTRODUCTION

Uncertainties, risks and the corresponding ranges in costs will directly affect how markets will adopt carbon sequestration technologies at the large scale. Characterizing risk levels based on how a system is expected to perform under both normal and adverse conditions will determine how well the system may perform its function. Specifically, a carbon dioxide (CO_2) capture, transportation and sequestration (storage) system is a complex and interdependent system. Testing the various parts of the system, the well bore integrity for example, will offer insights to the systems' components, yet may not fully account for various interaction effects (Covello and Merkhofer, 1993). These aspects of performance assessment are certainly not new, and many case studies involving waste disposal, natural gas storage, and specific projects offer substantial insight for large-scale (e.g., at scales sufficient to play a role in mitigating greenhouse gas emissions) carbon sequestration projects.

This report will first characterize the systems' various parts in ways not covered by the Borns et al. (2005) report, and then employ this information in an integrated systems model to more fully illustrate the overarching behavior (performance, economics) of a carbon sequestration system.

According to NETL (2006), there are three main types of carbon sequestration designations; geological, terrestrial, and in the ocean. The focus of this document will be on geological sequestration. Next, a listing of professional networking efforts has been developed to illustrate these efforts for carbon sequestration-related activities (Appendix 1). Lastly, a complete conference paper describing the Carbon Sequestration and Risk (CSR) model was developed in order to operationalize the systems information collected during the duration of this two-year study (Klotz et al., 2006a; 2006b). Appendix 2 briefly describes the model.

2. TYPES OF RISK ASSESSMENT

When discussing ‘risk’ in terms of projects, it is often helpful to more fully characterize the situation as either a ‘risk assessment’ or a ‘performance assessment’. The term ‘risk’ is one of a relative nature; what may seem risky to one individual may not seem so to another. The term ‘risk assessment’, however, can be more specific to a situation. Risk assessment allows one to appreciate the probability of an event occurring combined with their subjective view of how severe the respective consequences of that event are to their interests. Along these lines, a ‘performance assessment’ also adds a degree of realism by determining how a technology or situation behaves relative to some other known or understood quantity or entity.

This report addresses a few aspects of a performance assessment for carbon sequestration projects. It seeks to offer a general framework to look at an FEP, and potentially to offer a scenario-based set of suggestions to alleviate certain types of risks. To help characterize these aspects, a few definitions are in order. Specifically, the three main types of risk assessment relevant for carbon sequestration projects include; (1) Safety and Environmental risk, (2) Performance risk, and (3) Economic Risk. The purpose of this study is to *focus largely on performance risk and economic risk*. With this information, a larger systems-level understanding of clean coal and carbon sequestration systems will be developed for the research community involved with carbon sequestration issues.

Performance risk is the general risk a physical, geological or engineered system will not perform as expected or desired. For carbon sequestration systems, this could mean a carbon dioxide capture, transportation and storage system (e.g., in a geological formation) does not capture, transport or store (e.g., maintain a sufficient rate of injection into a formation, or leak rate from the formation) CO_2 in the desired manner. A key aspect of any geological storage project will be to assess how leaky the reservoirs may become over time. Storing CO_2 in a reservoir over time that eventually leaks some proportion of the total mass stored will become, in effect, another source of CO_2 to the atmosphere. This thereby negates some proportion of the sequestration project’s goal.

An example of a carbon capture and sequestration (CCS) system’s risk regarding performance goals is to maintain or move towards a global atmospheric CO_2 concentration with the assistance of large-scale carbon management systems. Specifically, Pacala (2001) analyzes how leaky reservoirs can be over time and still attain a global atmospheric CO_2 concentration of 450 or 550 parts per million (ppm) (corresponding to the S450 and S550 scenarios of the International Panel on Climate Change (IPCC) which address goals to curtail anthropogenic sources of CO_2). He finds that leakage limits are much less than one might expect due to the heterogeneity among reservoirs. If all reservoirs were identical, then a reduction in atmospheric CO_2 from 750 ppm to 450 ppm would require a mean leak rate of less than 0.1% per year, whereas due to their heterogeneity and subsequently different leak rates, a mean leak rate could exceed 0.1% per year and still meet this ppm goal. Pacala's work and the framework implemented in this analysis demonstrate that an overall carbon sequestration system can account for potential leaks within geological sinks and still achieve the desired levels of performance.

Economic risk for a carbon sequestration system is that associated with the system's ability to maintain cost targets relative to the desired performance objectives. Specifically, if alternative means of sequestering carbon dioxide, or avoiding emissions, develops a more cost effective way to meet the performance goals (e.g., carbon dioxide trading markets, energy conservation, technological progress for generating electricity, etc.) then the system may meet the performance goals with little economic risk.

3. AN ASSESSMENT FRAMEWORK

A framework often used to assess storage issues is the Features, Events and Processes (FEP) analysis methodology. The framework is useful when analyzing risks that may influence the safety of a storage system (Bowden and Rigg, 2004). Next, a scenario analysis develops to assess the general range of possible outcomes given a specific set of FEPs. After a high-level scenario analysis is developed, a more experimental process modeling (engineering or science-based) step identifies key aspects of the system (e.g., what chemical changes might one expect over the life of a geological sink storing substantial amounts of CO_2). Finally, Bowden and Rigg outline the fourth and final step, which is to perform/determine a consequence analysis. The final step helps determine what are the actions regulators might take to alleviate the risk if an event occurs (e.g., a health and safety-related event occurs). The FEP framework can also look towards long-term projects for risk analysis lessons.

> Like CO_2 sequestration, safe nuclear waste disposal requires understanding the complex, coupled physical-chemical-mechanical processes that will occur over periods of hundreds to thousands of years (Benson et al., 2002). However, underground disposals of nuclear waste differs in so many aspects from geological CO_2 sequestration. The physical and chemical features of nuclear waste, its potential effects and toxicity and the way nuclear waste is disposed (in waste canisters) make underground disposal of nuclear waste completely different than underground CO_2 sequestration. Moreover, nuclear waste is generally stored in rock-salt formations or deep clay deposits (Commissie Opberging Radioactief Afval, 2001). The lessons to be learned from underground disposal of nuclear waste should be found in the area of risk assessment methodology, monitoring, and public outreach.
>
> - Damen et al. (2003), pp. 13.

Damen et al. (2003) continue to describe the systematic process by which one can begin to assess a carbon sequestration project's system performance by employing the FEP framework.

> The systematic survey of FEP (features, events, and processes) developed in the nuclear waste area might be suitable to assess the long-term risks associated with underground CO_2 storage (Benson et al., 2002). The FEP framework is a procedure to identify, classify and screen all relevant features, events, and processes that may cause risks. Features refer to geologic features, such as stratigraphic layering and faults or fracture zones. Events refer to occurrences such as changes in precipitation fluxes, seismic activities, and mining enterprises. Processes refer to physical/chemical and other processes active at the site such as buoyancy flow of variable-density fluids and chemical-sorption. By combining critical FEPs, scenarios are constructed and selected for performance assessment (Benson et al., 2002).
>
> - pp. 13.

The FEP framework offers a useful methodology to assess geological storage of CO_2. While of paramount importance, geological storage is only one piece of the overall CO_2 sequestration system. Thus, building on the uncertainty surrounding geological CO_2 sequestration, figure 1 illustrates a higher-level framework that can incorporate the spirit of the FEP while continuing to address the overall system's view of a CO_2 capture, transportation and sequestration system from both the performance and economic risk assessment points of view.

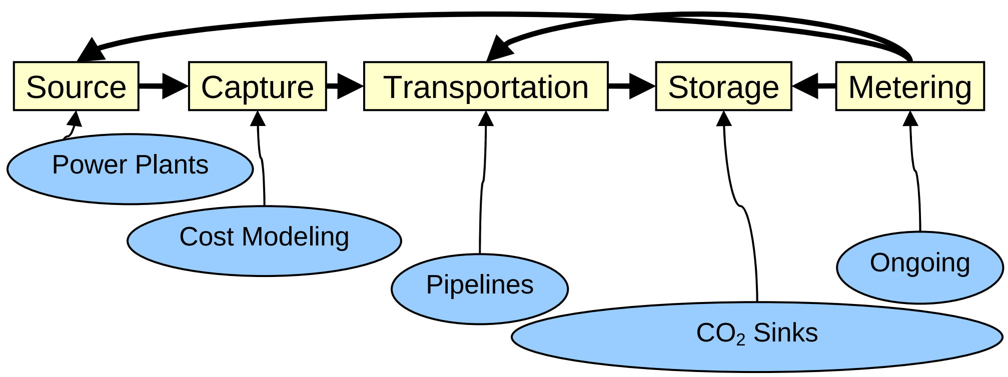

Figure 1. A Generic CO_2 Flow and Cost Model Structure.

This report examines the performance and economic risks involved with each of the general components represented in figure 1. The framework offers a clear, concise and transparent way to examine where the economic and performance risks lie within existing and potential technologies for removing CO_2 from power plant emissions. The Carbon Sequestration and Risk (CSR) computer model, developed as part of this project, builds on this overarching framework to assess performance and economic risk issues for both global and local (e.g., pilot project) scale scenarios. The following sections of the report outline a few key lessons from each of the system's topical components listed in figure 1.

3.1 Carbon Dioxide Sources and Capture Technologies

There is growing interest in capturing carbon dioxide technologies from the burning of fossil fuels. This interest has been spurred globally by concerns over greenhouse gas emissions. The research interest has been growing in the U.S. largely due to the Administration's Global Climate Change Initiative announced in 2002 (Bush, 2002).

3.1.1 Sources of CO_2 in the U.S.

Electricity Production Accounts for 39% of Total CO_2 Emissions in the U.S.

In the United States, 39 % of the total CO_2 emissions came from generating electricity in 2004. Figure 2 illustrates U.S. CO_2 emissions.

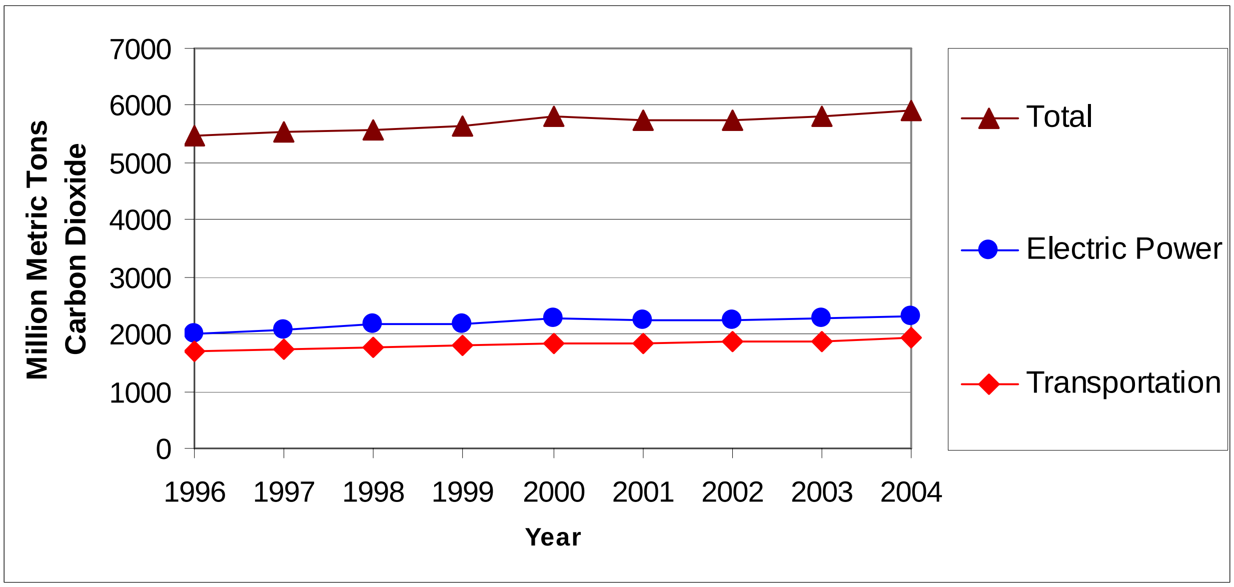

Figure 2. U.S. Carbon Dioxide Emissions by Select End Uses (EIA, 2006).

Emissions from electricity generation represent one of the 'low hanging fruit' amongst the many strategies to reduce emissions throughout the economy. Many of the capture technologies for existing power plants, and several technologies that may become more wide spread in the coming decades have been used at commercial scales in other industrial sectors. Thus, the confluence of greenhouse gas emissions concerns with relatively established technologies represents an opportunity to reduce CO_2 emissions from power plants. Figueroa et al. (2006), for example, estimates that by 2030, of the 88% of the total CO_2 emissions from power generation based on coal-fired power plants, 75 percentage points of this share will come from plants that exist today. In their analysis, they identified a target market of coal-fired power plants in the U.S. of 184 GW (out of 323 GW) that can achieve approximately 50% reduction in CO_2

emissions. Thus, there is an opportunity to retrofit existing coal-fired power plants in an effort to curtail CO_2 emissions.

Figure 3 illustrates the worldwide scale of the carbon dioxide emissions and potential sequestration issue.

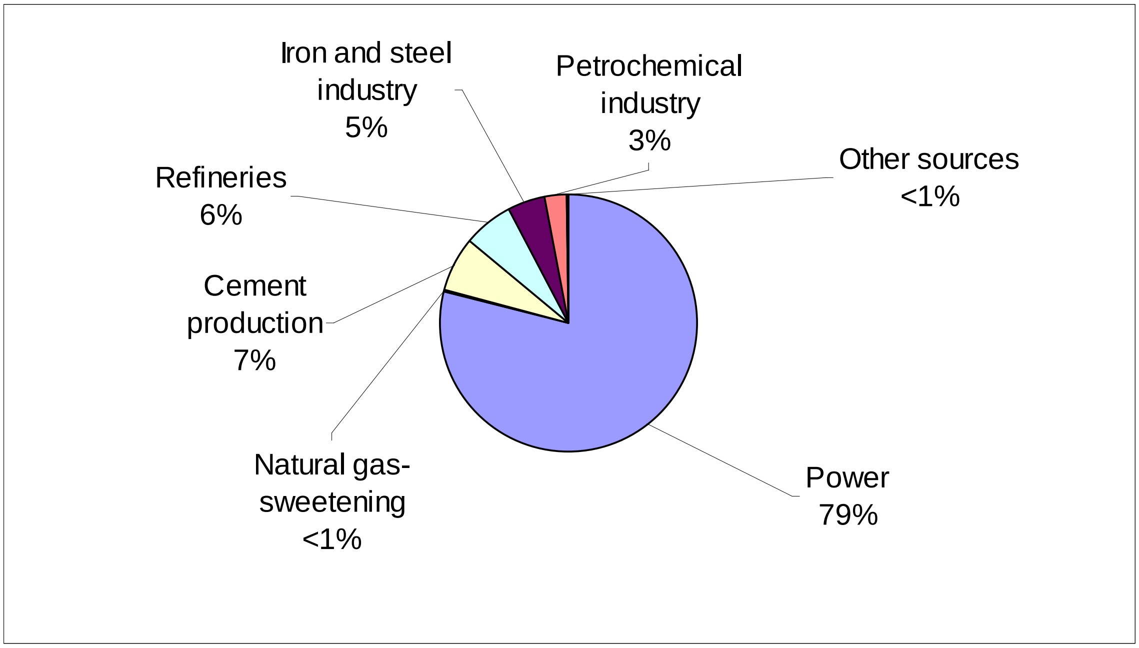

Figure 3. Worldwide Stationary Carbon Dioxide Emissions
(13,375 MtCO2 in 2002) (IPCC, 2005).

Globally, the annual emissions from power plants represented 79% of the global total stationary CO_2 emissions (13,375 $MtCO_2$) where coal-fired power plants represented 76% (7,984 $MtCO_2$) of the global power production (IPCC, 2006). The United States, for additional context, emitted 1,894 $MtCO_2$ in 2004 for coal-fired power plants (EIA, 2006). This represents approximately 14% of the global total CO_2 emissions, and a substantial opportunity to potentially lead the world market in carbon capture and sequestration technologies for the purposes of carbon sequestration.

3.1.2 Capture Technologies

CO_2 Capture and Sequestration Will Increase the Price of Coal-based Electricity

Should existing power plants look towards retrofit technologies, or should utilities wait to build new plants that can more easily capture carbon dioxide? Should industry invest in new technologies when, in the United States, there is no federal mandate limiting carbon dioxide emissions and developing countries may not limit their own CO_2 emissions? These are some of the key questions driving CO_2 sequestration politics and the subsequent industry's concerns in the carbon capture community today.

A report by White et al. (2003) describes three main options that are being explored to address greenhouse gas levels in the atmosphere: (1) increasing overall energy efficiency, (2) utilizing less carbon-intensive sources of energy, and (3) carbon sequestration with current and future energy sources. The first point applies generally to increasing the overall fuel consumption and electricity production efficiencies for existing and to-be-developed technologies. The second point applies more generally to cleaner fuels or fuel switching (e.g., coal to natural gas). The last item points towards carbon sequestration as one method to address CO_2 emissions while continuing to use relatively plentiful or desirable fuel resources (e.g., domestic coal or natural gas, respectively) to generate power.

Along these lines, retrofitting existing coal-fired power plants represents a good opportunity to deploy carbon capture and sequestration technologies on a large scale. With this opportunity, however, come several challenges. First and foremost are the cost increases for both the capital, and the subsequently derived electricity due to capturing the CO_2. Secondly, there can be a substantial loss in the power plant rating due to the parasitic energy requirements necessary to capture the CO_2 at the power plant.

Figure 4 illustrates several technologies and there respective capital costs both before and after installing carbon sequestration technologies [Natural Gas Fired Combined Cycle (NGCC), Integrated Gasification Combined Cycle (IGCC), Supercritical (SC), Pulverized Coal (PC), Ultra-Supercritical (USC)]. These relative costs demonstrate that capital costs increase by 90, 36, 73 and 67% for the respective technologies.[1]

[1] These cost comparisons are to illustrate the increase in capital (and subsequently electricity) costs when using carbon capture technologies. As described in NETL (2005), great care should be taken to appreciate the differences in the assumptions behind cost calculations, technologies, and other salient parameters when comparing carbon capture technology costs across studies.

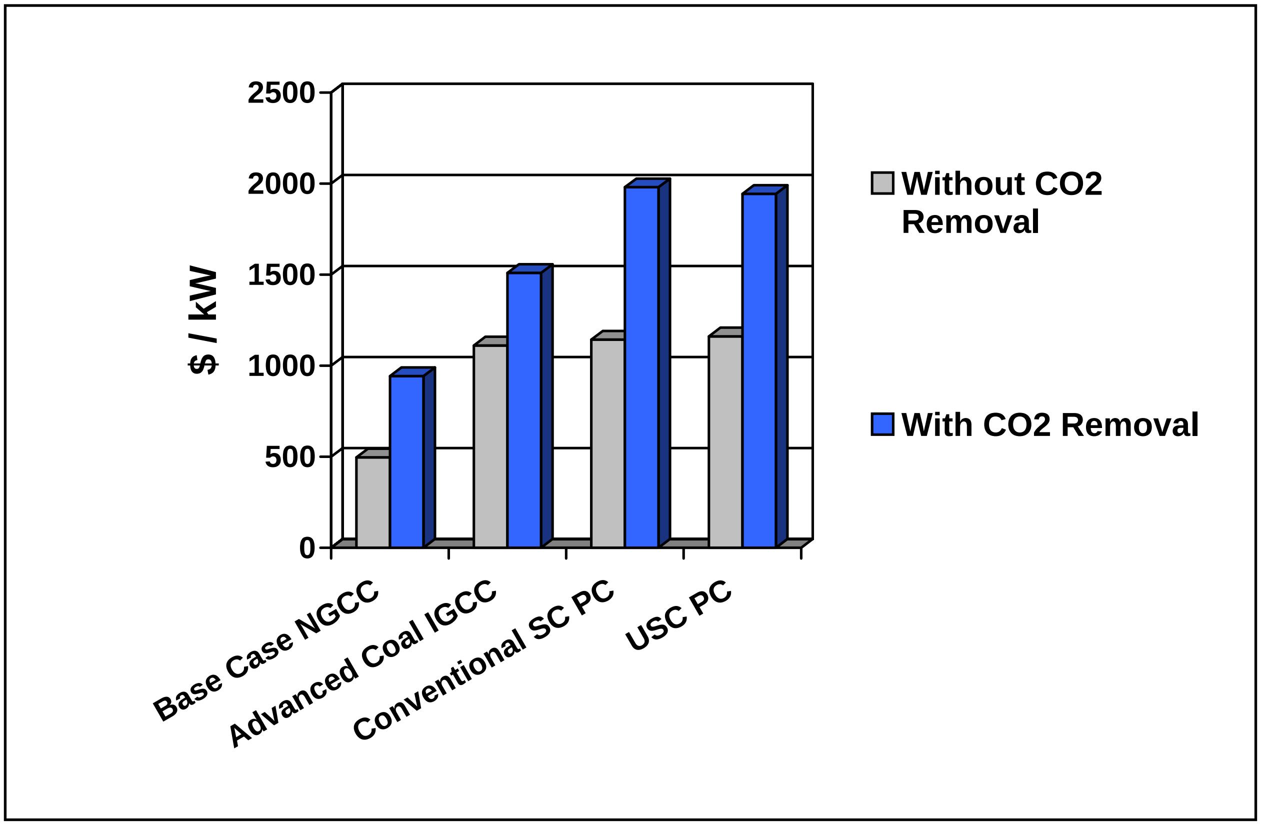

Figure 4. Technology capital costs for generating electricity with and without CO_2 capture (DOE / EPRI, 2002).

Energy penalties due to CO_2 capture are not trivial. Current MEA technology for coal-fired power plants incurs a 30 to 40 percent energy penalty. When scaled up across 184 gigawatts of installed capacity (a level consistent with the number and types of power plants in the U.S. that may adopt this technology nationally in the Untied States), this leads to an additional capacity requirement of 98.5 and 153.3 GW, respectively (Figueroa et al., 2006). To put this potential increase in capacity into perspective, this would translate into approximately 197 to 307 additional 500 MW sized power plants that would need to be built in the United States just to make up for the energy losses due to capturing CO_2. Additionally, these levels of additional power will require some 308,338 to 479,637 thousand tons of coal (Figueroa et al., 2006). The rail capacity within the United States faces congestion today, and may run at or near capacity for coal shipments (Smith and Machalaba, 2006). With this potential increase in the coal required to help meet the nation's electricity demand (not including growth in demand), the need to reduce the parasitic loads due to carbon capture technologies is very large indeed.

Figure 5 illustrates both the energy penalty and relative electricity cost increases across electricity generating technologies when carbon dioxide capture systems are considered.

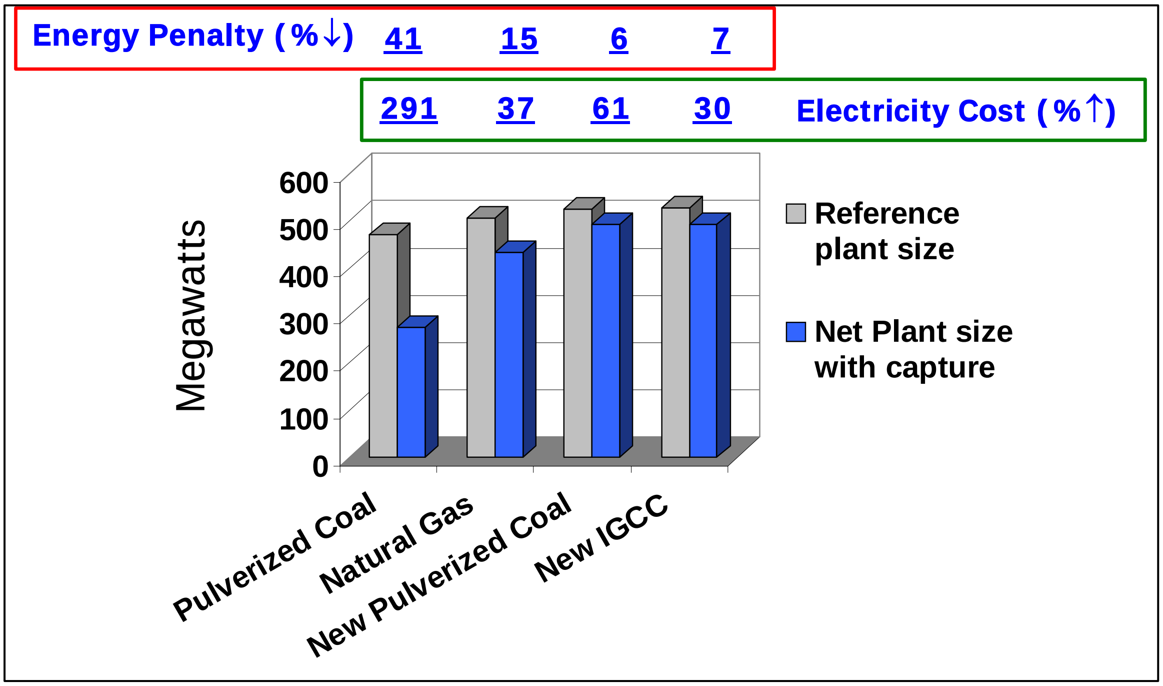

Figure 5. Select Power Generating Technologies, Increased Cost of Electricity and Decreased Megawatt Rating due to Parasitic Energy Losses from Carbon Dioxide Capture Systems (IPCC, 2005; based on Rao and Rubin, 2002; Rubin et al., 2005).

Figure 5 shows new IGCC technology using coal can be a more economical method to capture carbon dioxide than retrofitting existing pulverized coal plants. Thus, as current pulverized coal-based plants (and its general class of technology) come to the end of their respective lifetimes, an opportunity may exist to replace them with IGCC power plants to further the technology and gain additional performance and economic history for IGCC-based plants.

According to industry experts (Rao and Rubin, 2002), the common MEA-based CO_2 absorption system is one of several technologies that has been successfully used to remove large amounts of CO_2 from flue gas streams. Originally developed to remove acidic gas from natural gas, the MEA systems are now at the forefront of the commercial, market-tested technologies used and/or considered at the large scale for removing CO_2 from flue gases. Given the existing coal-fired power plants produce approximately 53% of the electricity in the United States, the industry may adopt the proven MEA technology to retrofit existing plants (EIA, 2006). While retrofitting existing power plants may be less economical than waiting to install IGCC technology, the retrofit analyses are being developed. Figure 6 illustrates a systems study of a coal-based electricity plant with an MEA capture system with multipollutant control (Rao and Rubin, 2002).

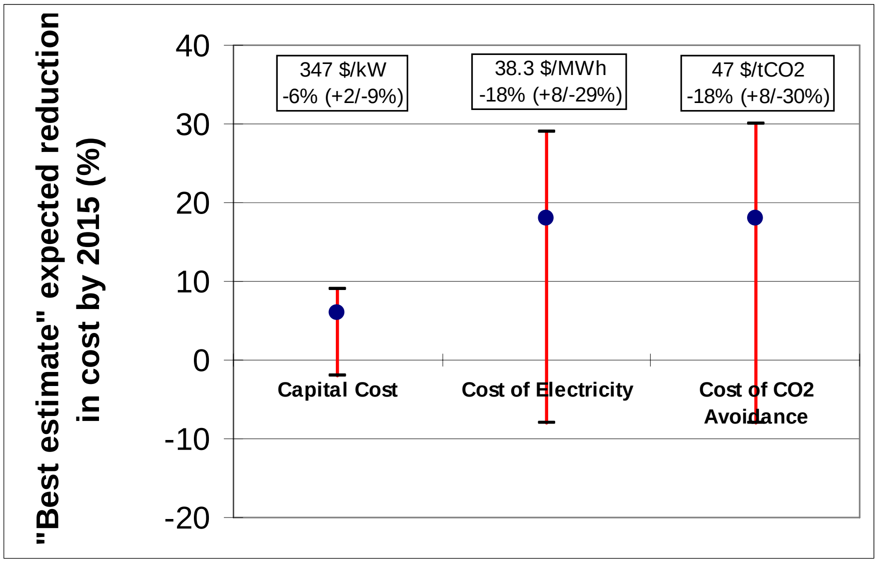

Figure 6. A range of potential percentage decrease in key MEA-based CO_2 capture system parameters based on an expert panel (Rao and Rubin, 2002).[2]

Rao and Rubin (2002) describe their survey of the carbon sequestration technology research community's general cost assessment for capital cost, the cost of electricity, and the cost of CO_2 'avoided' (e.g., the actual cost to capture CO_2 on a $/tonne basis, which also includes the cost of replacing any generating capacity lost during the process of capturing CO_2) in the coming decades. The range of 'best estimate' information from their survey highlights the underlying fact that the technologies may cost more than forecasts suggest today. Alternatively, the overall system's costs may decrease substantially if additional economic incentives begin to play a role when selecting projects (e.g., enhanced oil recovery efforts using CO_2 injection yield an economic benefit by producing additional petroleum to offset the increased capital costs).

Figure 7 illustrates ranges of CO_2 avoided costs for both Integrated Gasification Combined Cycle (IGCC) and Pulverized Coal (PC) technologies for power plants. It is important to note that IGCC technology is largely more efficient than PC technology and therefore the costs per ton of CO_2 avoided is less.

[2] The initial costs are given above each respective parameter, and the range illustrates the variation amongst the expert's best estimates.

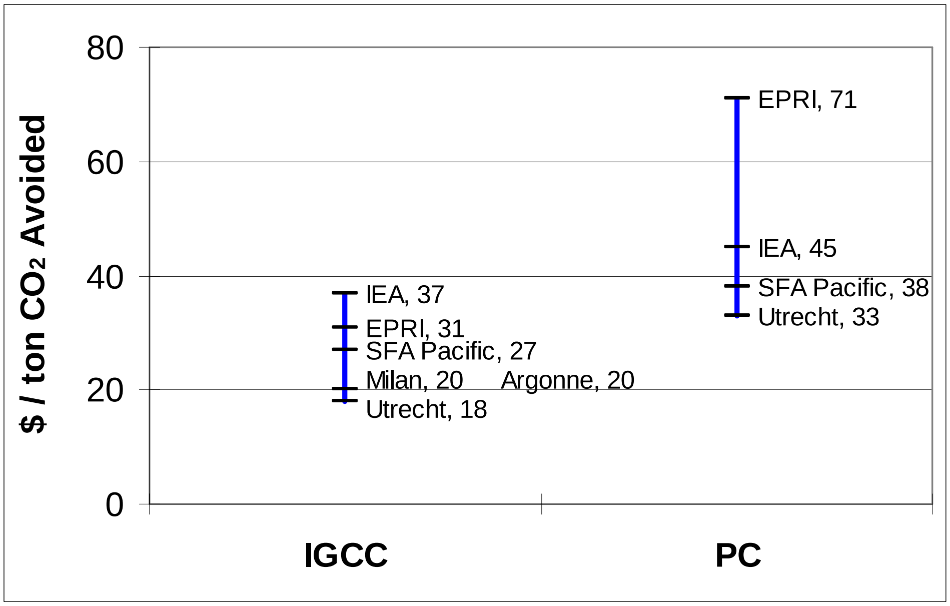

Figure 7. Avoided Carbon Dioxide Capture Costs from Integrated Gasification Combined Cycle (IGCC) and Pulverized Coal (PC) Plants
(adapted from David, 2000).

3.2 Transportation

Transporting CO_2 in pipelines is a proven technology. The oil extraction industry has been using CO_2 for enhanced oil recovery purposes for decades. Figure 8 illustrates several existing CO_2 pipelines in the Southwestern United States.

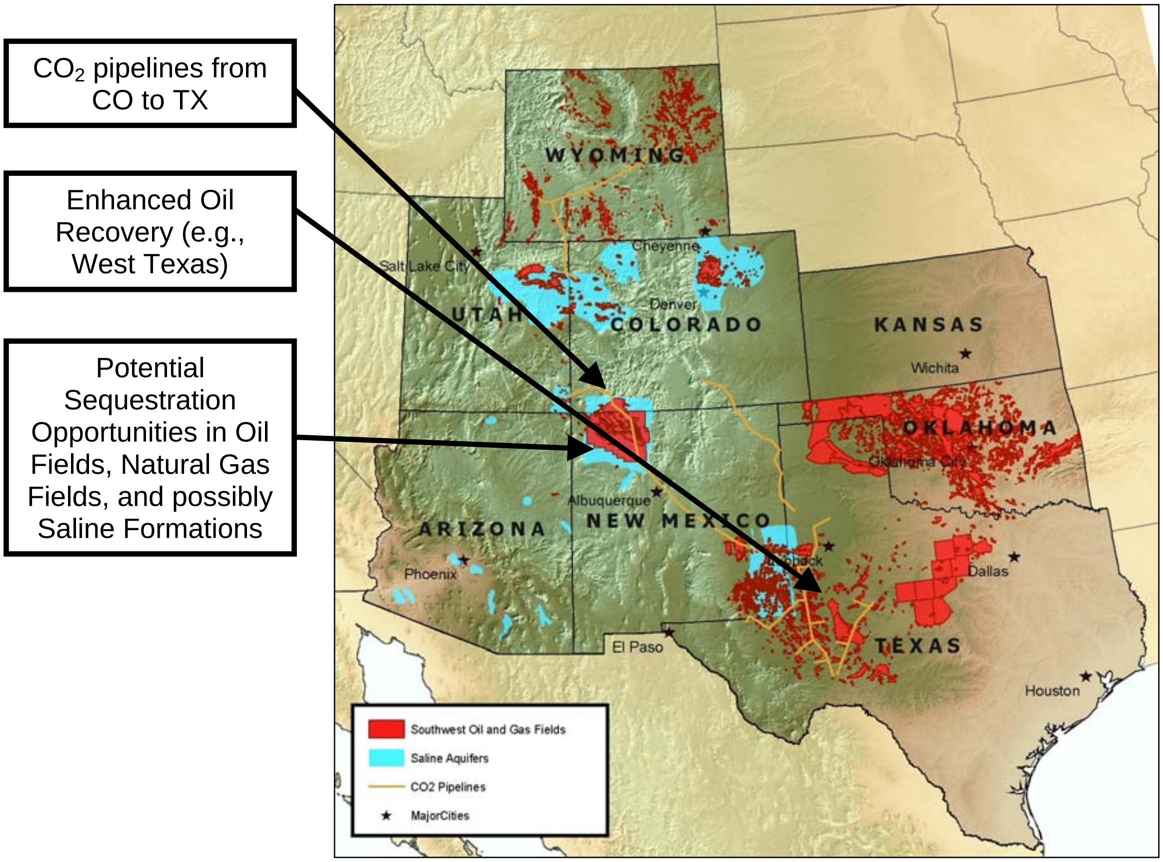

Figure 8. Existing CO_2 Pipelines in the Southwestern United States (Biediger, 2006).

One of the more important drivers toward building a CO_2 pipeline network is the right-of-way concerns. A CO_2 sequestration system involving pipelines without a clear and uncontested right of way will likely not be built. Thus, from a systems view the nonmarket, institutional factors (e.g., federal and state laws, public perception) are extremely important to account for while addressing the performance and economic metrics throughout the analysis. Accounting for these issues in a cost and benefit framework, however, may be challenging in the face of evolving rules, regulations and public perception issues regarding large-scale storage of CO_2 underground.

Some studies take a more direct method to calculate the capital costs of CO_2 pipelines as a first step towards larger-scale infrastructure development. These formulae illustrate one method often used to calculate the cost of CO_2 transmission pipelines, disposal wells, and surface piping for a potential geological sequestration system (Ogden, 2002; Williams, 2002; adapted from Borns et al., 2005)).

CO_2 Transmission and Disposal =
Cost of pipeline (C_{PT}) +
Cost of Disposal Wells (C_{DW}) +
Cost of Surface facilities (C_{SF}). Eq. (1)

C_{PT} = (Base Cost of pipeline transmission * ((Current flow rate / Base flow rate) ^ 0.52) * ((Transport distance / Base transport distance)^ 1.24)) Eq. (2)

Base Cost of pipeline transmission = $3.51 million per tonne (t) of CO2
Current flow rate = 445.9 tonnes CO_2 per hour (t/h)
Base flow rate = 445.9 tonnes CO_2 per hour (t/h)
Transport distance = 100 kilometers (km)
Base transport distance = 100 kilometers (km)

C_{DW} = Number of wells *(Initial Capital Cost ($1,000,000) + [($381/foot)*depth of wells (feet)]) Eq. (3)

[A well has an initial capital cost (fixed cost) of $1.0 million (Williams, 2002 per Ogden, 2002). Williams (2002), 1 km = $1.25 million/km for drilling costs, 1 km = 3280.833 feet. $1250/meter. ($1250/meter / 3.280833 feet/meter) ≈ $381 /foot.]

3.3 Storage

As described in Borns et al. (2005), a systems analysis of carbon sequestration technologies must also account for the relative size of the CO_2 sink(s) both locally (for pilot projects), and globally (for potential atmospheric CO_2 concentration management strategies). Table 1 illustrates the relative potential capacity for various kinds of carbon sinks.

Table 1. Relative Orders of Magnitude for Global CO_2 Storage Capacity Estimates (Table adapted from Herzog, 2001; utilized by Borns et al., 2005).

Sequestration Option	**Worldwide Capacity**
Ocean	1000s GtC
Deep saline formations	100s – 1000s GtC
Depleted oil and gas reservoirs	100s GtC
Coal seams	10s-100s GtC
Terrestrial	10s GtC
Utilization	< 1 GtC / yr

The analysis presented in Appendix 2 offers a more detailed integration of this information for the overall CO_2 system's analysis based on Klotz et al., 2006.

3.4 Measurement, Monitoring and Verification of CO_2

Including high-level measurement, monitoring and verification (MMV) costs is an extremely important and evolving component of CO_2 systems analysis studies. The public acceptance aspects toward storing large quantities of CO_2 underground for a project are paramount when considering project transparency and liability as they relate to economic and performance risk. As the MMV technologies evolve, care must be taken to insure that performance metrics are met (e.g., detect CO_2 at a ppm concentration to a level in line with avoiding potential problems with the storage system). De Figueiredo et al. (2005) highlight the notion that if the purpose of CO_2 storage is to reduce atmospheric levels of CO_2 then a well-planned project (or strategy) must be developed.

> A second source of liability is associated with leakage from geologic storage reservoirs and its effect on climate change. Assuming that carbon emissions will be controlled under a regulatory regime in the future, there will be a liability associated with leakage. If the effective storage time is thousands of years, that liability would probably be negligible. On the other hand, if the effective storage time is only decades, carbon storage is probably not worth the effort because it is doubtful that the benefits of such a short storage time can justify the extra costs associated with storage. However, if the effective storage time is in between, questions arise as to how to account for this liability. As an example, Herzog et al. (2003) developed a framework that can be used to determine the economic value of what we term climate liability. They conclude that this liability is best addressed as part of a broad climate policy that is enacted to control greenhouse gas emissions.
>
> - De Figueiredo et al., 2005, pp. 647-657.

Along these very lines, the work shown in Appendix 2 addresses times scales on the order of hundreds of years to highlight the salient performance and economic risks and goals relevant toward greenhouse gas (CO_2) emissions. The analysis in Appendix 2, as well as those by Kobos et al. (2005a, b, c; 2006a, b, c, d, e) draw on the work of Benson et al. (2004) to include MMV costs on projects ranging from \$0.16 to \$0.31 per tonne of CO_2. This allows the project to include the potential range of MMV costs within the overall systems analysis.

4. CONCLUDING REMARKS

The purpose of this two-year project was to characterize existing carbon capture and sequestration technologies at a high level, develop an analytical framework, and implement the framework in a system dynamics model. The first year of this project succeeded in characterizing the existing technologies to help focus the analysis on power plant technologies that may be amenable to carbon capture technology. For additional details, see the report, "Carbon Sequestration and Clean Coal Technologies: Characterizing Systems and Evaluating Costs" by Borns et al. (2005). The assessment also helped determine which capture technologies are largely accepted by the carbon capture research community as relatively proven technologies (e.g., MEA technology), and to help lay the foundation for an analytical framework for energy models using system dynamics.

The Carbon Sequestration and Risk Model (CSR) was developed using the lessons learned from the first year of this study, and information gathered in concert with that for the Southwest Regional Partnership (SWP) on Carbon Sequestration project. In the SWP project, another system dynamics model developed in Powersim Studio has the ability to rank sequestration sites based on size, distance from the CO_2 source (e.g., power plants), and can dynamically create a hypothetical CO_2 pipeline network for sequestration based on a innovative variation on what is commonly referred to as a minimal spanning tree algorithm (Kobos et al., 2006d). Many of the same resources were utilized between the two projects (e.g., literature review, cost metrics for technologies and sink sizes, etc.), which helped develop a growing place for Sandia National Laboratories in the carbon sequestration research community as outlined in Appendix 1. Additionally, with the CSR model's abilities, the framework can interrogate existing information regarding the relative size of geological reservoirs used for sequestration, and can include variations on existing power generation technologies (e.g., coal or natural gas power plant technology today, in the future, using different assumptions regarding the plants' technical attributes such as its lifetime, etc.). In summary, this project collected and characterized existing carbon sequestration system's metrics, increased Sandia National Laboratories' presence in the carbon sequestration research community, and developed a system dynamics model to operationalize this information in a systematic way to enhance current and potentially future CO_2 sequestration analytical projects and energy systems analyses.

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APPENDIX 1. DEVELOPING A PLACE IN THE CARBON SEQUESTRATION RESEARCH COMMUNITY.

Event	Date	Item	Purpose	Location
NETL Visit	10/25/2004	Presentation	Networking in CO_2 Sequestration (Seq.) community	Pittsburg, PA
International Association for Energy Economics (IAEE)	9/19/2005	Presided over the session, and presented a paper	Leveraging LDRD with the Southwest Regional Partnership on Carbon Sequestration (SWP), Presented a paper on the SWP. Kobos presided over the session on CO_2 and Energy	Denver, CO
CO_2 Seq. Workshop	10/25/2005	Workshop Coal bed methane & Terrestrial Seq.	Leveraging LDRD with SWP	Albuquerque, NM
Conference	11/3/2005	MIT Carbon Sequestration Forum VI	Learn New Research, Networking	Cambridge, MA
Global Warming Workshop	11/15/2005	Seminar on Emissions from China and India	Networking in the energy policy community	Washington, D.C.
Materials Research Society (MRS)	11/30/2005	Invited Speaker	Presentation, CO_2 sequestration in System Dynamics models	Boston, MA
SWP	12/15/2006	Presenting the Integrated Assessment 'String of Pearls' Model	System Dynamics and CO_2 sequestration model	Socorro, NM
News Article, Lab News	1/20/2006	Quoted with Borns and others	Increasing CO_2 seq. research awareness at SNL and beyond	Sandia National Laboratories
NETL Conference	5/8/2006	Presented a Conference Paper	Networking in CO_2 seq. community	Alexandria, VA
Electric Power Research Institute (EPRI) Workshop	3/22/2006	CO_2 Capture & Transportation Workshop	Gave 2 presentations on CO_2 capture	Palo Alto, CA
Phase I Report (SWP), Annual SWP Report	3/8/2006 12/21/2006	SWP report, NMT/DOE report	Phase I Report, Annual 2005 SWP report, Ongoing presence in the CO_2 sequestration community	SW CO_2 Partnership
IAEE	9/27/2006	Presenting 2 papers, Presiding.	CSR model paper, SWP paper, Kobos presiding over a CO_2 and energy session	Ann Arbor, MI

National Energy Technology Laboratory (NETL); Carbon Dioxide (CO_2); Laboratory Directed Research and Development (LDRD); Sandia National Laboratories (SNL); New Mexico Institute of Technology and Mining (NMT); Department of Energy (DOE); Carbon Sequestration and Risk Model (CSR).

APPENDIX 2. INTEGRATING THE SYSTEM'S ANALYSIS: THE CARBON SEQUESTRATION AND RISK MODEL

The Carbon Sequestration and Risk (CSR) Model is a user-friendly, high-level dynamic simulation model that quantifies performance and economic effectiveness of carbon sequestration using geologic storage. The performance risk assessment accounts for whether enough carbon dioxide (CO_2) can be sequestered over the years to offset emissions from power generation in addition to any CO_2 that may leak from previously sequestered CO_2. Additionally, the model accounts for capacity limits in the geological formations used for CO_2 sequestration. The model assesses economic risk by determining whether particular types of technologies that capture CO_2 from power generation are able to do so in an economically-sound manner. The net present value (NPV) serves as the metric to determine whether technologies or strategies (e.g., employing a Carbon market permit trading scheme) may help attain certain economic goals. Lastly, the model has two scales to assess these technologies and strategies; at the global scale with respect to atmospheric concentration of CO_2 in parts per million (ppm), and at a single project scale in line with using one power plant to a single CO_2 sink. The information presented in this appendix is an abridged description of the extended model structure descriptions, scenarios and results found in Klotz et al. (2006a).

Several key features of the model include:

- Written in Powersim Studio 2005, a dynamic simulation software package, and runs on a laptop, licensed by www.powersim.com
- Driven by power plant carbon dioxide emissions and the corresponding sequestration, transportation and storage costs.
- Easy to use interface screens that allow the user to explore "What-if?" questions regarding power plant technologies, CO_2 sequestration sink capacity scenarios, and other opportunities using both sequestration in concert with a permit market trading scheme for CO_2 to reduce the overall system's Net Present Value (NPV) costs.
- Global and single plant systems scenarios can be developed to address global atmospheric CO_2 concentration goals, as well as single-plant economics insight, respectively.

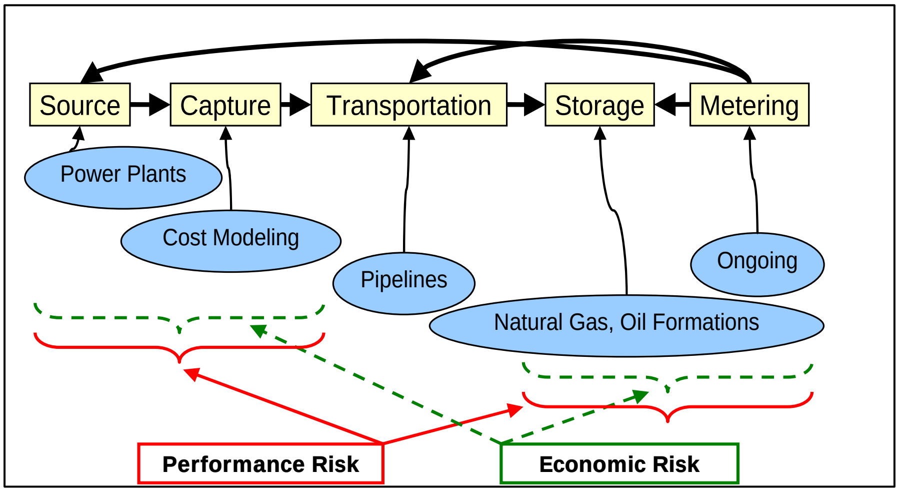

Figure A2.1. The general model structure with performance and economic risk assessment.

Global Modeling

The interest in reducing carbon dioxide emissions, both on a global scale and at a single plant scale, is growing. Carbon dioxide capture and sequestration (CCS) provides one option for reducing CO_2 from generating electricity and other sources. One advantage of CCS is that it allows the economy to utilize fossil fuels, while limiting CO_2 emissions to desired levels. Using fossil, often domestically-based, fuels for electricity production may offer a low cost option for reducing atmospheric CO_2 without substantial fuel-switching.

The performance and economic risk of various sequestration and market options to reduce global (and small-scale) CO_2 emissions are developed from a systems-level view. The performance risk of geologic storage, for example, lies in whether or not enough storage capacity exists to sequester the required stocks of CO_2 necessary to meet global atmospheric concentrations of CO_2. Additionally, geologic formations used for storage may leak over time. It is therefore paramount to both include any leaks in the emissions budget, as well as maintain monitoring technologies required to recognize and address the leaks where necessary. Economically, the risks to the system are determined by calculating the NPV cost of sequestration in leaky storage as compared to the NPV of permanent sequestration with no leaks. Addressing economic risks are necessary to determine which strategy (leaky storage, permanent storage, employing a permit market system) is deemed the lowest cost solution while maintaining a performance standard for the system.

The CSR model was designed to help the user determine whether carbon capture and storage in geologic reservoirs could effectively limit CO_2 emissions while addressing the system's performance and economic criteria. The user can adjust the assumptions for sequestration cost, discount rate, storage leak rate, and carbon permit price. Additionally, the user can switch between single plant and global sequestration schemes which allows for many scenario combinations to be developed and analyzed. The CSR model quantifies the conditions necessary for carbon sequestration to meet economic and performance goals.

The CSR model quantifies the conditions by calculating two effectiveness metrics: the performance effectiveness, and the economic effectiveness. Performance effectiveness is calculated in two ways. First, the performance effectiveness for sequestration is determined by calculating how many years' worth of emissions can be held in storage if CO_2 is only captured directly from fossil fuel-based electricity plants. If and when the CO_2 storage sink is full, the system can no longer store CO_2, and the performance effectiveness of the system is compromised. Second, the amount of CO_2 which leaks from previously stored CO_2 must also be captured and stored each year. When the total amount of CO_2 that needs to be captured (e.g., any leaking CO_2 from previously stored CO_2) exceeds the amount of expected CO_2 emissions, then sequestration can no longer meet the allowable emissions goals and the performance effectiveness of the system is compromised.

Economic effectiveness compares the NPV of storage in leaky storage capacity relative to permanent sequestration. Permanent sequestration is defined as either storage in a sink (oil and natural gas formations) without any leaks. Along with the NPV economic effectiveness metric, additional system's costs (e.g., the relative cost of various systems' components) are calculated to give additional insight to the economic risk. The model presents the total cost over 300 years, along with the marginal cost per ton of CO_2 for each scenario.

Global Results

The CSR model's global reference case assumes that expected future emissions will lead to an atmospheric CO_2 concentration of 750 ppm, and expects sequestration to limit the atmospheric concentration to 450 ppm. Storage is assumed to take place in used oil and natural gas reservoirs, so total storage capacity is 0.9 trillion tons. The global clearing price for a CO_2 permit is assumed to be a constant 40 $/ton and the discount rate is a constant 2%.

Limited geologic storage capacity reduces the number of years which carbon sequestration alone could keep the atmospheric concentration of CO_2 at the 450 ppm level. All global storage capacity would be used after 140 years in the reference scenario if only oil and natural gas formations were utilized to capture the global electricity production's CO_2 emissions. In order for the reference scenario to be effective for at least 300 years, 1.57 trillion tons of additional storage capacity would be required. Storage in other types of potential sinks, especially in oceans and deep saline formations, could provide the additional capacity for many more years. If the necessary capacity was available, sequestration would be effective for 300 years if the average leak rate from geological formations used to storage CO_2 was below 0.13%.

The model also includes a permit market for CO_2, similar to the spirit of the Kyoto Protocol, which accounts for each ton of CO_2 such that when it is permanently stored, a permit for that ton could be sold, thereby offsetting the sequestration cost by the selling price of the permit (e.g., $40/ton CO_2). Sequestration systems using leaky reservoirs with an average leak rate of 0.01% per year to address this 450 ppm scenario would be 60% as economically effective as purchasing 40 $/ton permits to offset the cost of sequestration. The total cost of sequestration at this leak rate would be 16 trillion NPV dollars. If storage took place in reservoirs with an average leak rate of 0.12%, the scenario would be 56% as economically effective as purchasing 40 $/ton permits and would cost 18 trillion NPV dollars. That is, systems with lower leak rates will tend to be a more cost-effective solution for sequestration. Alternatively, using the permit market system in concert with sequestration in sinks with low leak rates (e.g., 0.01%/year) will lower the cost of sequestering CO_2 even further because the selling price of the permits offsets some of the sequestration costs.

Changing the discount rate can have a substantial impact on the results of the model (table A2.1). For the reference global scenario, the average cost of sequestration, assuming a discount rate of 1%, is 28 $/ton (NPV). Permanent sequestration using permits would only cost 13 $/ton at the same discount rate. If the discount rate is set to 5%, then the average cost of sequestration in leaky storage and permanent sequestration are essentially the same at a NPV of 2 $/ton. For the reference global scenario, a lower discount rate will cause permanent sequestration using permits to be the most cost effective option compared to storage in leaky reservoirs. At higher discount rates, sequestration in leaky reservoirs becomes economically similar to permanent sequestration using permits.

Table A2.1. Discount Rate Sensitivity Analysis

Discount Rate (%)	Economic Effectiveness (%)	Leaky (NPV$/ton)	Permanent (NPV$/ton)
1	47	28	13
2	60	10	6
3	70	5	4
4	77	3	2
5	83	2	2
6	88	1	1
7	92	1	0.9
8	96	0.8	0.7

Note: Global Reference Scenario – Assumes homogeneous sink system with an average leak rate of 0.01%, and economic effectiveness is a comparison with permits. Permit price is assumed to be a constant 40 $/ton.

If the goal is to limit atmospheric concentrations of CO_2 to 550 ppm, storage in leaky geologic capacity becomes a more effective option. This is partially due to the fact that achieving 550 ppm of CO_2 is a more lenient strategy than trying to achieve 450 ppm of CO_2. Consequently, storage in natural gas and oil reservoirs would last for 233 years as compared to 140 in the 450 ppm strategy. If roughly 1 trillion tons of storage capacity was available globally the 550 ppm strategy would last even longer, up to 300 years. From a performance standpoint, sequestration would be effective if storage takes place in capacity with an average leak rate below 0.23%. Economically, sequestration at these high leak rates would be more expensive than buying 40 $/ton permits. Assuming a constant discount rate of 2% and an average leak rate of 0.23%, sequestration in leaky reservoirs would cost 10 $/ton (NPV), while purchasing permits would cost only 6 $/ton (NPV). Thus, using the market-based CO_2 permit option in concert with sequestering CO_2, a similar amount of CO_2 reductions to the atmosphere can be achieved at a lower overall cost.

Single Power Plant to Sequestration Sink Modeling

The CSR model can also assess the effectiveness of carbon sequestration at the single plant scale. The user can select the type of electricity generating technology [old pulverized coal, old natural gas, new pulverized coal, new Integrated Gasification Combined Cycle (IGCC)] the model uses along with the amount of CO_2 the plant emits each year. The reference case plant is an existing 470 MW pulverize coal plant with an amine-based retrofit system for capturing the CO_2. To meet select performance and economic goals, this plant would be able to limit emissions to 1 million tons of CO_2 ($MtCO_2$) per year if 650 $MtCO_2$ of storage capacity were available and the storage capacity had a leak rate below 0.11%. The model offers a more detailed cost of sequestration breakdown for the single plant's components such as the technology costs for capture at the plant, pipelines, disposal of the CO_2, and additional surface piping and metering costs. The total cost of sequestration for an existing coal plant is over 72 $/ton, with capture costs making up the majority of the total (67 $/ton).

For additional context, if a 527 MW IGCC plant was limited to 1 $MtCO_2$ of emissions per year, it would require 660 $MtCO_2$ of storage capacity with an average leak rate below 0.11% to be effective for 300 years. The cost of sequestration is substantially less than the existing coal plant, at roughly 30 $/ton (with an approximate cost breakdown of capture (80%), pipelines (18%), disposal (1%) and metering (1%)). At a 2% discount rate and assuming storage capacity has a 0.01% leak rate, limiting the existing coal plant to 1 $MtCO_2$ of emissions per year would have an average cost of 12 $/ton (NPV), and would permanently sequester 641 $MtCO_2$. A new IGCC plant with the same restrictions, however, would have an average cost of 5 $/ton (NPV) while permanently sequestering 661 $MtCO_2$. Thus, IGCC technology is a more cost effective solution to sequester CO_2 in many cases than existing coal-fired power plants.

If a carbon emissions permit trading scheme were employed, the sequestration goals can be achieved at a relatively low cost (or even no cost) option over the sequestration period of performance (table A2.1). For example, limiting the IGCC plant to an emissions level of 1 $MtCO_2$ per year could potentially have economic benefits through sequestration in somewhat leaky CO_2 sinks if permit prices were set to at least 40 $/ton. This is due to the market forces at work; if emitters of CO_2 can reduce (or sequester) their emissions more cheaply than a competing emitter while both are active in the permit market, then there is an economic incentive for those who are more efficient at sequestration to sell available permits to less-efficient emitters of CO_2. If permits cannot be used to offset sequestration costs, then it would cost an IGCC plant a total of $3 billion NPV. If the clearing price for permits was at 40 $/ton, then the IGCC plant would profit $1 billion NPV while limiting emissions. Therefore, in many circumstances, a permit market system can help achieve a desired performance goal at an overall lower cost.

Table A2.2. Permit Price Sensitivity Analysis

Permit Price ($/ton)	Marginal Cost (NPV, $/ton)	Total Cost (Billion NPV $)
0	5	3
10	4	2
20	2	1
30	.2	.1
40	-2	-1
50	-3	-2

Note: New 527 MW IGCC Plant Scenario– Assumes homogeneous sink system with an average leak rate of 0.01%. Discount rate = 2%.

Figure A2.2 illustrates the model prototype's introductory screen.

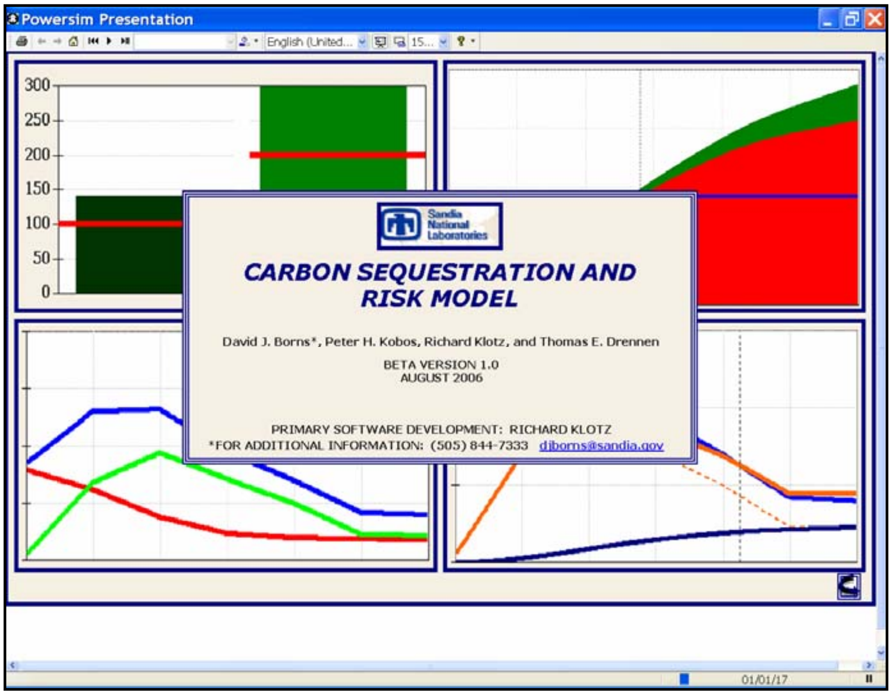

Figure A2.2. The Introductory Screen of the Carbon Sequestration and Risk Model (CSR).

Additional Information

For additional information regarding the Carbon Sequestration and Risk model's scenarios, assumptions and results, see Klotz et al., (2006a, b).

APPENDIX 3. OVERVIEW OF POWER AND CARBON CAPTURE TECHNOLOGIES.

This appendix lists the major categories of technology for the power sector and carbon dioxide sequestration relevant for both pilot and potentially larger scale carbon capture projects. The work by Rao and Rubin (2002) offers an extremely useful topology of the technologies relevant to carbon dioxide capture from power sources. As the carbon capture community continues to define technology 'winners' that may help reduce carbon emissions from power sources, these types of assessments at the high level will help determine which technologies are mature both from a technical standpoint (not in the R&D stage, but rather close to, or already commercially ready), and a marketability one as well. In other words, these topologies allow interested parties the ability to perform high level performance and economic risk assessments across technologies in a transparent manner.

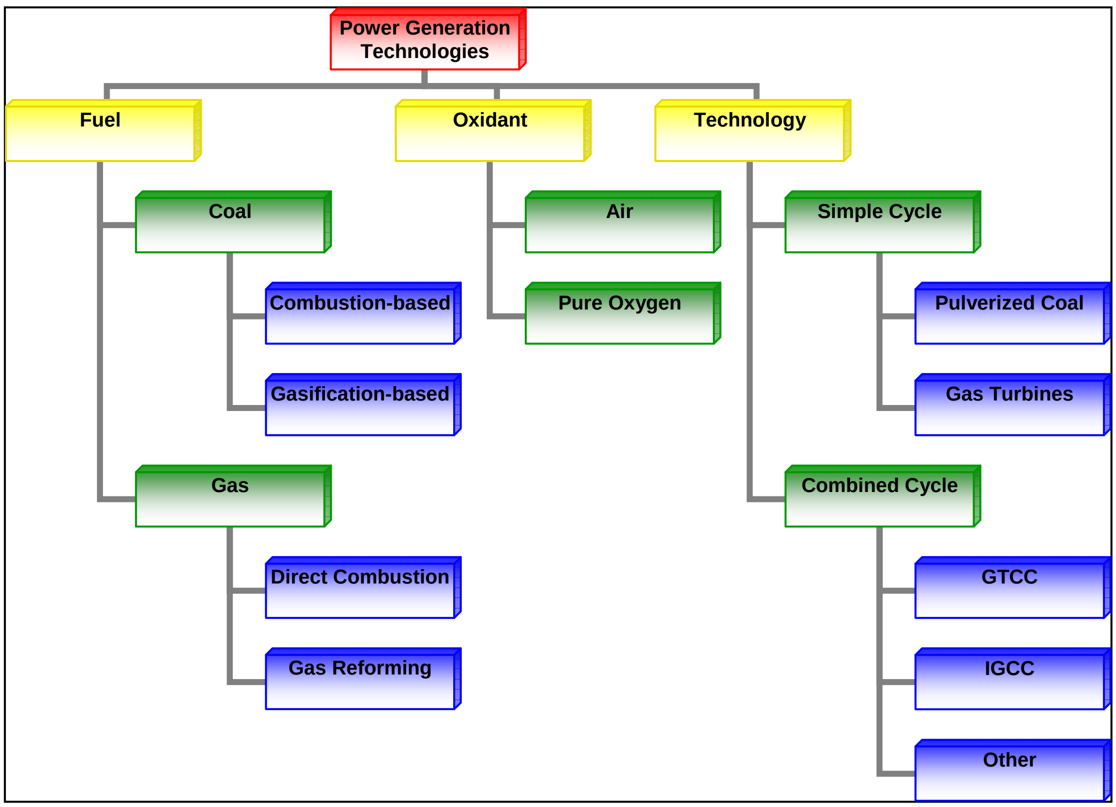

Figure A3.1. Fossil-fuel Based Electricity Generation Technologies Sorted by General Fuel, Oxidant and Technology Categories (adapted from Rao and Rubin, 2002).

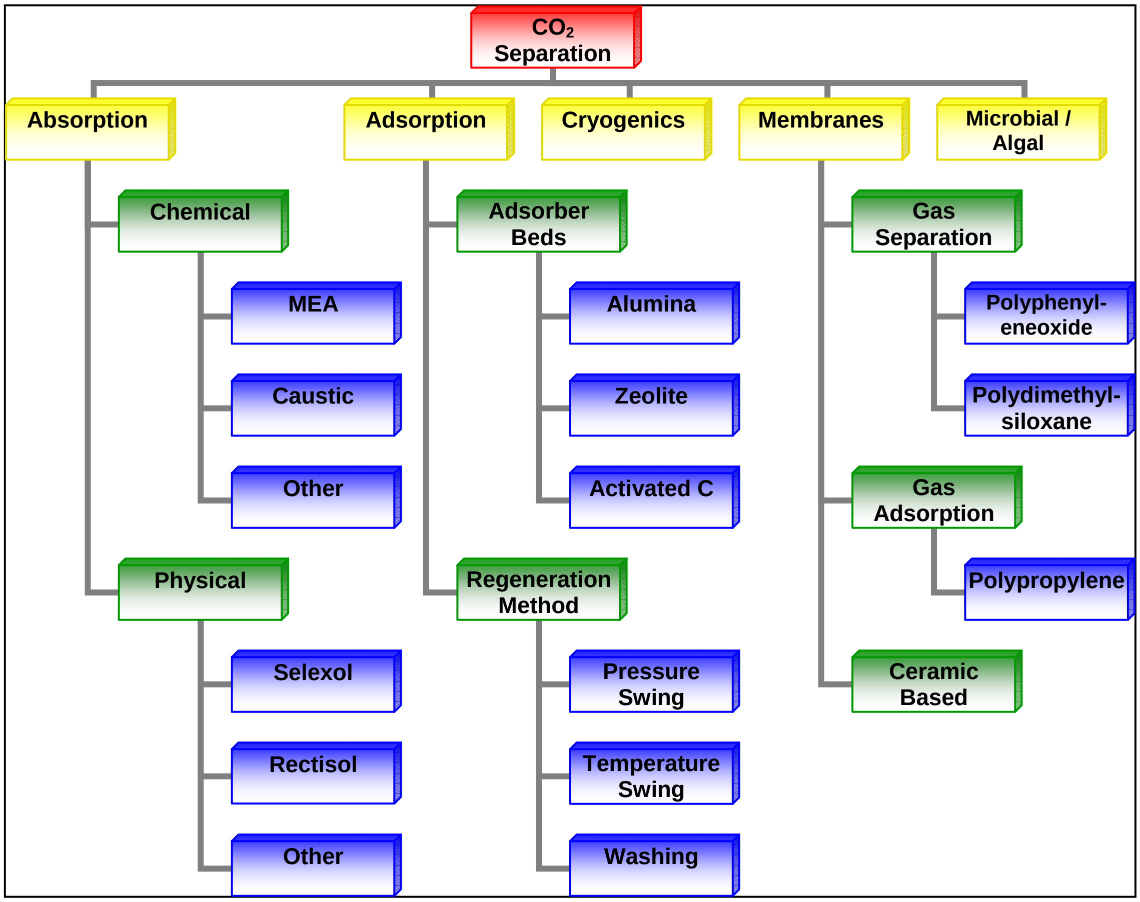

Figure A3.2. CO_2 separation and capture technologies
(adapted from Rao and Rubin, 2002).

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