Sequestering Carbon from Power Plants: The Jury is Still Out
By
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ABSTRACT

This thesis utilizes the MIT Emissions Prediction and Policy Analysis (EPPA) model to analyze the economic potential of carbon capture and sequestration (CCS) power plant technologies. Two of the most promising technologies are implemented in the US region of the EPPA model. One technology is based on a natural gas combined cycle (NGCC) capture plant and one is based on an integrated coal gasification combined cycle (IGCC) capture plant. Although the cost of using CCS technologies is relatively expensive under today's prices in the economy, the economic conditions for the CCS technologies could change as policies are enacted to reduce greenhouse gas emissions. By analyzing several different policy scenarios, the conditions under which the CCS technologies could enter the market are presented. This thesis shows that CCS technologies can be economical under some situations. Furthermore, by explaining the modeling methodology and results one can understand the implications for using this modeling approach for policy analysis.

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"If you want the right answers, don't ask the model---ask your mother."

--John M. Reilly

"If you want to lose your credibility instantly, just start off your presentation [to your client] by saying, "the model says . . ."

--Professor John Sterman

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List of Acronyms

AEEI	Autonomous Energy Efficiency Improvement
BAU	Business-as-usual
CCS	Carbon Capture and Sequestration
CES	Constant Elasticity of Supply
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
COP	Conference of Parties
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPPA	Emissions Prediction and Policy Analysis model
UNFCCC	United Nations Framework Convention on Climate Change
GAMS	General Algebraic Modeling System
GREEN	General Equilibrium Environmental model
GTAP	Global Trade Analysis Project
GtC	Billion Tonnes of Atmospheric Carbon
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
MEA	Monoethanolamine
MIT	Massachusetts Institute of Technology
MPSGE	Mathematical Programming System for General Equilibrium analysis
NGCC	Natural Gas Combined Cycle
OECD	Organization for Economic Cooperation and Development
O&M	Operations and Maintenance
ppm	Parts Per Million
psi	Pounds per Square Inch
SAM	Social Accounting Matrix
T&D	Transmission and Distribution

1 Introduction/Problem Statement

Scientists have understood for at least a century that the earth's atmosphere could warm as carbon dioxide concentrations in the atmosphere increase, but it was not until the 1970's that people started to fear the consequences of increased anthropogenic emissions of greenhouse gases. In the late 1980s, the concerns of scientists coincided with widespread drought, an unusually warm summer in the United States in 1988 and the heightened concern about the ozone hole. The ratification of the Montreal Protocol to address ozone depletion provided hope that the issue of global warming could also be addressed. In 1990 the decision to negotiate a climate agreement was made in the United Nations General Assembly, and the Framework Convention on Climate Change was drafted in time for signature at the United Nations Conference on Environment and Development in Rio de Janeiro in 1992. The objective of the Convention is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992). After a series of meetings by the Conference of Parties (COP) the nations agreed upon the Kyoto Protocol in 1997 as a step "in pursuit of the ultimate goal of the Convention" (United Nations, 1997). The Kyoto Protocol set emission targets to be met by Annex B countries ("developed" countries and economies in transition) by the time period 2008 to 2012.

As nations develop policies to meet these targets a debate has been forming about how to best reduce emissions. There appears to be little consensus in the debate as to what future emissions will look like and what policy actions are likely to do to these emissions predictions. As with the climate issue generally, expert opinion varies considerably as to which policies are appropriate and what level of action is needed. There are some technologists who see technical possibilities of reducing emissions and argue that "no-regrets" policies exist. They argue that emissions can be reduced easily in today's economy by driving more efficient cars, expanding the use of combined heat and power, and using more efficient appliances. All that is needed is more information, the implementation of better technology, and a transformation of the way we think about waste, energy and resources. On the other hand, many economists argue that prices of goods will need to change to give the proper incentives for economic actors to reduce emissions and that in general actions to reduce emissions will require costs. The different opinions are rooted in different beliefs about how the economy, society and technology interact. Much of the difference in views reflects the fact that the group of technologist and the group of economists are asking much different questions: "Economists who build energy models want to forecast the future of the economy and its response to changes in energy prices while technologists are interested in technical possibilities" (Victor and Salt, 1994). As a result, modelers, economists, and scientists use much different tools to analyze the policies that will achieve the emissions reduction targets. For example, technologists often try to study ways to "fill the gap." The gap is simply the discrepancy between the projected emissions and the emissions reduction target. Technologists fill the gap by trying to assess how different technologies can contribute to reducing emissions from the projected level to the targeted level. Economists use economic models that try to determine how much prices need to change for emissions to reach the target level. The results from the two methodologies can be quite divergent, and it is fair to say that the two camps are not always receptive to the views of the other, even though they may recognize that each approach has its merits.

This thesis seeks to add to this policy debate by discussing the economics of carbon capture and sequestration technologies. The carbon capture and sequestration technologies analyzed in this thesis will only be those that produce centralized electric power. The analysis will build upon the current knowledge that has been derived predominantly from the technologist camp, and use this information to introduce the technology into an analysis tool from the other camp, a macro-level economic model.

Understanding that this is not the easiest task, the thesis starts out by trying to at least ask the right questions or frame the analysis in the correct manner. This thesis will not try to seek the "right" answer about the economic feasibility of the technologies. Instead, it will try to frame the results in such a way that those who read it will understand the results and be able to decide for themselves. To do so, it is important to understand the role of economic modeling. Modeling efforts seek to increase the knowledge on a particular issue for the purposes of improving one's decision-making ability. According to Parson and Fisher-Vanden (1997), models "seek to combine knowledge from multiple disciplines in formal integrated representations; inform policy-making, structure knowledge, and prioritize key uncertainties; and advance knowledge of broad system linkages and feedbacks." Works by Reilly (1991), Sterman (1988), Parson and Fisher-Vanden (1997), Wilson and Swisher (1993), and Meadows *et al*. (1982) give extensive discussions about the role of models, suggested criteria for models, the various types of models, and the strengths and weaknesses of different modeling approaches. Reilly (1991) states that "it is not possible to develop a single model that does everything well and to try to do so produces models that may be equally good at everything but not very good at anything." Sterman (1988) suggests that models cannot be judged by whether or not the results can be verified, but rather how well they serve their intended purpose.

This thesis will present a partial equilibrium and a general equilibrium approach to analyzing the carbon capture and sequestration technologies. The merits and shortcomings of both will be presented. In doing so this thesis seeks to combine bottom-up engineering knowledge with top-down economic knowledge, inform decision-makers about the potential of CCS technologies, and advance general knowledge on feedbacks and linkages affecting technical choice.

2 The Technology

Two carbon capture and sequestration technologies for power generation are studied here, one based on natural gas combined cycle (NGCC) plants and one based on integrated coal gasification combined cycle (IGCC) plants. The term Carbon Capture and Sequestration (CCS) as used in this thesis refers only to these fossil power technologies and the subsequent sequestration of the captured carbon dioxide. A myriad of other sources and capture processes are often considered under the umbrella of carbon capture and sequestration technologies, but this thesis does not analyze these options. Instead, the thesis gives a brief overview of other carbon capture and sequestration technologies and focuses on the economics of the two CCS technologies.[1]

Technologies that capture carbon dioxide are not new or exotic. The absorption technology for capturing carbon dioxide from natural gas streams was developed more than 60 years ago to produce a more pure natural gas stream. The technology of capturing carbon dioxide from a power plant's flue gas was first implemented more than 20 years ago. When the price of oil rose in the late 1970s, owners of oil wells created a demand for carbon dioxide for use in enhanced oil recovery (EOR). Carbon dioxide's ability to increase the productivity of an oil reservoir created value for the CO_2. In response, several commercial CO_2 capture plants were constructed in the United States (Herzog and Vukmirovic, 1999). As the price of oil fell in the mid-1980s most capture plants shut down. However, the North American Chemical Plant in Trona, CA, which was built in 1978, still produces CO_2 to carbonate brine for the use in producing soda ash. Other plants have been subsequently built for other commercial purposes and over a dozen are in use today for various purposes across the globe.[2]

The heightened concern about global change has created renewed attention for capture technologies, this time for the purposes of decreasing CO_2 concentrations in the atmosphere. Projects are already underway to research and implement such carbon capture and sequestration technologies in the countries like the United States, Japan, Norway, and Great Britain.

In the United States the Department of Energy (DOE) has started to evaluate the economic, technological, and social issues of carbon sequestration technologies. The U.S. research effort into CO_2 capture and sequestration technologies has spent over $10 million since 1989. This is a small amount compared to the total annual expenditure on global change research of $1.6 billion (Herzog, Drake, and Adams, 1997). In 1993 the DOE contracted with the Massachusetts Institute of Technology to analyze the research needs for the capture and sequestration of carbon dioxide emitted from fossil fuel-fired

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[1] This chapter relies heavily on work done by Howard Herzog, Principal Research Engineer at the MIT Energy Laboratory. For a more detailed information on CCS technologies, see Herzog, Drake, and Adams, (1997); Herzog, (1999); and Herzog and Vukmirovic, (1999).

[2] See Herzog and Vukmirovic, (1999) for more detail and references on the history of carbon capture and sequestration technologies.

power plants (Herzog *et al*., 1993). In 1997, the President's Committee of Advisors on Science and Technology (PCAST) underscored the importance of carbon sequestration research and recommended increasing the DOE's R&D for carbon sequestration. Specifically the report recommends:

> A much larger science-based CO2 sequestration program should be developed.... The aim should be to provide a science-based assessment of the prospects and costs of CO2 sequestration. This is very high-risk, long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful (PCAST, 1997).

The goal of the DOE is to develop "practical sequestration technologies with costs as low as \$10 per ton of carbon" (\$10/t C is equal to \$2.7/t CO_2)[3] (DOE, 2000).

In Japan, the Tokyo Electric Power Company (TEPCO) formed a global environment team in July 1989 and a Global Environment Department in April 1990 to strengthen its research efforts to solve the problem of global warming (TEPCO, 1994). Established within the Global Environment Department are laboratories performing research on carbon dioxide removal, storage, and use technologies.

In Norway, Statoil has been a pioneer in terms of actually implementing carbon sequestration technologies. Statoil has been separating CO_2 from natural gas using standard amine absorption technologies during extraction processes at the Sleipner West gas field. Statoil sequesters the CO_2 800 m beneath the North Sea into a large, deep saline aquifer (IEA, 2000b). Approximately 20,000 tonnes/week have been sequestered since September 1996 in response to the Norwegian government's \$50/ton CO_2 tax.

An effort in Great Britain at the International Energy Agency (IEA) Greenhouse Gas R&D Programme seeks to enhance collaborative research and disseminate information on carbon capture and sequestration technologies. The program, which started in 1991, seeks to

- Identify and evaluate technologies for reducing emissions of greenhouse gases arising from use of fossil fuels;
- Disseminate the results of these studies;
- Identify targets for research, development and demonstration and promote the appropriate work (IEA, 2000c).

The IEA Greenhouse Gas Programme is working to put carbon capture and sequestration

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[3] The shadow price of carbon emissions can be expressed in \$/ton C and \$/ton CO_2. Engineers generally use \$/ton CO_2 and economists generally use \$/ton C. One \$/ton CO_2 is

technologies in perspective with other methods of reducing greenhouse gas emissions.

Using carbon capture and sequestration technologies is but one of many strategies that could reduce the effects of global warming. Some look to ways of producing energy with fewer emissions via new and improved supply technologies like nuclear, biomass, solar, wind, geothermal, hydroelectric, fuel cells, more efficient fossil, or combined heat and power. Other improvements can come on the demand side with improved efficiency of end-use devices and conservation of energy. All of these approaches need to be considered, and I will consider the carbon capture and sequestration technologies as a complement to these strategies.

2.1 Overview of Carbon Capture and Sequestration Technologies

The following paragraphs describe the many sources and technologies for carbon sequestration and how the technologies that are evaluated in this thesis fit in. Carbon can be captured from multiple sources including industrial processes (ammonia and ethylene—which generate nearly pure CO_2 streams), refineries, power plants, natural gas operations (commercial gas fields may contain up to 20% CO_2 by volume), and production of hydrogen rich fuels (hydrogen or methanol—fuels that could be used in fuel cells). Carbon capture and sequestration technologies can be categorized as follows: 1) Natural Sinks, 2) Separation and Capture, 3) Storage, and 4) Reuse. The IGCC and NGCC power generation technologies that I consider in this thesis fall under the "Separation and Capture" category, but I do not explicitly state which technologies will be used to store or use the captured carbon dioxide. I rely on work by Herzog (1999) to determine an average cost of sequestration and/or usage, assuming that most of the CO_2 will be sequestered in geologic or ocean storage.

2.1.1 Natural Sinks

The options in this category are based on the improvement of the natural flux of carbon between the atmosphere and biosphere. Such concepts as planting trees, halting deforestation, improving soil management, and growing phytoplankton in the ocean are ways to sequester carbon from the atmosphere into trees, soils, and the ocean. Barriers to

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equivalent to 3.67 \$/ton C. This thesis will use \$/ton CO_2 throughout.

employment of these options include the operational cost of implementation, the opportunity costs of land use, the difficulty in measuring the actual carbon sequestered, and for oceans, concerns about the environmental implications. Policy makers and policy analysts are discussing the feasibility of these options as well (Watson *et al*., 1996; DOE, 2000; Rosenberg *et al*., 1999).

2.1.2 Capture Technologies

Carbon can be captured using different methods. To date, all commercial CO_2 capture plants use processes based on chemical absorption with a monoethanolamine (MEA) solvent (Herzog, Drake and Adams, 1997). The gas capture plant considered in this thesis is based on a NGCC plant that uses an MEA absorption technology. The coal capture plant is based on an IGCC plant that integrates a physical absorption process into the gasification process to capture the carbon dioxide. The physical absorption process is a better option due to the lower energy requirements. It can be used in the gasification processes because of the higher partial pressure of CO_2 compared to flue gases. Other processes like membrane separation, cryogenic fractionation, and adsorption technologies are also possible to separate the carbon from the flue gases, but "they are even less energy efficient and more expensive than chemical absorption" (Herzog, Drake, and Adams, 1997).

In absorption processes, the flue gas is continuously passed through the liquid solvent, which absorbs the CO_2. The CO_2 is then released by raising the temperature or lowering the pressure. Typical chemical solvents are amine or carbonate based, such as monoethanolamine (MEA), diethanolamine (DEA), ammonia and hot potassium carbonate (IEA, 2000a). The physical absorption process is similar and typically uses solvents such as Selexol® (dimethylether of polyethylene glycol) and Rectisol® (cold methanol) (IEA, 2000a). These processes are deemed to be the most economical and energy efficient of the capture technologies (Herzog, Drake and Adams, 1997). For a description of separation option using membrane separation, cryogenic fractionation, and adsorption, see the International Energy Agency Greenhouse Gas Programme's article "Carbon Dioxide Capture from Power Stations" (IEA, 2000a).

2.1.3 Geological/Ocean Storage

Once CO_2 is captured, one may sequester it in active oil wells for enhanced oil recovery (EOR), deep saline aquifers, depleted oil/gas wells, or the deep ocean. Each option still needs research to determine the costs of sequestration, the storage integrity, the technical feasibility, the environmental issues, and the public acceptance. The following table states the estimated worldwide capacities for these storage options, but these estimates are very uncertain. The worldwide total anthropogenic carbon emissions are about 7 GtC per year. Of this total, about 1.5 come from the United States and about 0.5 come from the US power production.

Table 1. Order of Magnitude Estimates for the Worldwide Capacity of Various Sinks

Sequestration Option	Order of Magnitude Estimate for Worldwide Capacity (GtC)
Active oil wells (EOR)	10
Deep Saline Formations	100 to 10,000
Oil and Gas Reservoirs	100 to 1000
Ocean	1000 to >100,000

Sources: Herzog and Vukmirovic, 1999; Herzog, Drake, and Adams, 1997; Watson *et al*., 1995.

Enhanced oil recovery would be an inexpensive option with good storage integrity, and it has been used in the past. Part of the sequestration costs would be offset by the value of the oil recovered, which depends on the price of oil. The amount of CO_2 that could be sequestered this way is small. The IPCC estimated that about 1% of annual anthropogenic CO_2 emissions could be used for enhanced oil recovery (Watson *et al*., 1995).

Storage in depleted oil and gas reservoirs is a viable option in terms of its cost, storage integrity, and capacity. The cost is judged to be less than \$3/t CO_2[4] (Watson *et al*., 1995). These reservoirs have already proven their ability to contain pressurized fluids for a long period of time and worldwide capacity is judged to be on the order of 100 GtC (100 billion tonnes) of atmospheric carbon (Herzog, Drake, and Adams, 1997; Watson *et*

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[4] The actual number used in the report was \$11/t C, which is equivalent to \$3/t CO_2.

al., 1995). In fact, depleted oil and gas reserves appear to be the most promising land storage option in the near term (Drake et al., 1993).

In the longer term, deep saline aquifers may be the best storage option (Herzog, Drake, and Adams, 1997). These aquifers are almost ubiquitous. Sequestration costs have been estimated to range from \$7 to \$30/t C (IPCC, 1995). However, the storage integrity is uncertain.

The biggest available sink is unquestionably the ocean. The effectiveness of storage as well as environmental impacts are big issues that will need to be addressed before the ocean is a viable option. Such issues are being researched.

2.1.4 Utilization/Chemical Fixation

One could utilize the carbon dioxide in industrial processes, for producing carbonate minerals, or for conversion to fuel. Not all are permanent sequestration options, and none of these options promise to be economic at a scale that would contribute to reducing the large amounts of CO_2 produced from power generation. Industrial usage, even when one is optimistic about the costs, could use only about 5% of the 1.7 billion tonnes of CO_2 produced annually from U.S. power plants (Herzog, Drake and Adams, 1997). Using CO_2 to produce carbonate minerals, really a form of geological sequestration, is a very costly option. This process sequesters carbon dioxide in carbonate minerals by enhancing the natural sequestration of CO_2 onto alkaline rocks. Doing so is an energy intensive process because it requires the handling of a large quantity of rock. Conversion to fuels would also be costly.

2.2 Technical Description of CCS technologies

The power generation technologies evaluated in this thesis are based on existing, commercially available natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) power plants with modifications for capturing CO_2. Herzog (1999) identified these technologies as two of the most economically promising power plant options available. They are only two of the many possible technologies available to capture CO_2 from power plants. One can modify power plants to capture CO_2 by using a variety of the methods described previously. The modifications to the IGCC and NGCC plants as studied in this thesis are described below.

- The coal capture plant is based on coal-fired IGCC power plants. In these plants, coal is gasified to produce syngas (hydrogen plus carbon monoxide). The syngas is cleaned and shifted ($H_2O + CO \Rightarrow CO_2 + H_2$), followed by the removal of CO_2 with a physical absorption process. The hydrogen rich gas left behind is used to fuel a combined cycle power plant.
- The gas capture plant is based on NGCC power plants. In these plants, the natural gas drives a gas turbine. Steam to drive a steam turbine is produced by recovering heat from the gas turbine exhaust, as well as some additional natural gas firing. The CO_2 is removed from the flue gases with an MEA scrubbing process (Herzog and Vukmirovic, 1999).

No specific sequestration or utilization options are evaluated in this thesis. Instead I assume a mixture of the sequestration options will be used at a constant marginal cost of \$10 per ton CO_2 for sequestration.

2.3 *Partial Equilibrium Analysis of the CCS Technologies*

This analysis seeks to provide a framework for analyzing the economics of electricity production from CCS technologies. It is termed “partial equilibrium” because the costs are based on engineering studies that assume constant prices for inputs and outputs. The costs are categorized in terms of busbar costs, CO_2 sequestration costs, electricity transmission and distribution costs, and carbon emissions costs. The busbar costs include all costs incurred in the production of the electricity at the plant site and the capture and compression of the CO_2 to 2000 pounds per square inch (psi). The sequestration costs include all costs incurred in transporting the CO_2 from the plant site to the point of injection, either underground or in the ocean. The transmission and distribution costs include the costs of transporting the electricity from the power plant to the point of end use. Emission costs per kilowatt-hour are computed from the emissions per kilowatt-hour and the carbon price.

2.3.1 *Busbar Costs*

The busbar costs used in this analysis rely on work by Herzog and Vukmirovic

(1999). Their analysis compares several published economic and engineering analyses of carbon capture and sequestration technologies. They use a composite model to calculate the costs of several different technologies with and without capture technology. Technologies based on NGCC and IGCC power plants are judged to be the most economical.

The analysis illustrates how capital, fuel, and operation and maintenance (O&M) input costs change from plants without capture technology (reference plants) to the plants with the technology to capture CO_2 (capture plants). These cost increases result from the parasitic effects of CO_2 separation on the electricity generation process. Separation requires energy to capture and pressurize the carbon; therefore, a power plant that used to produce 400 MW of electricity may now only produce 350 MW after modification for the capture process. Thus, a capture plant requires more fuel, labor, and capital to produce the same amount of power output. The table below shows the cost and emissions data for the NGCC and IGCC plant with and without capture.

Table 2. Busbar Costs (mills/kWh) and Emissions Data (kg CO_2/kWh)

	Reference		Capture	
	NGCC	IGCC	NGCC	IGCC
Capital	12	30	26	39
FUEL	18	10	21	12
O&M	2	6	6	8
Total	32	46	53	59
Emissions	0.37	0.74	0.04	0.09

Source: Herzog, 1999

2.3.2 Sequestration Costs

The sequestration costs are assumed to be \$10/tonne CO_2. At this level, sequestration costs add 5-10% to the busbar costs. The gas and coal capture plants must pay 3.6 mills/kWh and 8.1 mills/kWh, respectively, for sequestration costs.[5] Sequestration costs for coal plants are higher because more CO_2 is captured per kWh due to the higher carbon intensity of coal compared to gas.[6]

We know that the costs of sequestering CO_2 depend on the distance to and the nature of the sequestration option. The power plant may be right on top of an underground sink and the CO_2 has value for use in EOR, resulting in low sequestration costs. In other instances, the CO_2 may need to be transported over 1000 km for injection in the ocean, resulting in much higher sequestration costs. Although the sequestrations costs may vary, the majority of options are judged to cost between \$5 and \$15/ ton CO_2 and thus \$10/ton CO_2 is appropriate for a general approximation (Herzog, 1999; Herzog *et al.*, 1997)

2.3.3 Electricity Transmission and Distribution Costs

Transmission and distribution costs are assumed to be 20 mills/kWh. As with sequestration costs, transmission and distribution (T&D) costs can vary depending on the regulatory structure and the distance from the power plant to the customer. The T&D costs are based on numbers from the Energy Information Administration (Beamon, 1998). The T&D costs are mentioned separately so to ensure that they are purposely considered when comparing two technologies.

2.3.4 Emissions Costs

The capture process captures about 90% of the carbon dioxide from the fuel; therefore, a CCS technology will still need to pay for some emissions when there is a carbon price. The cost of emissions is a product of the emissions and the carbon price. In equation form, the costs are presented as:

$$EC = k \times P_{CO2}$$

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[5] See Appendix for calculations.

[6] Carbon intensity can be defined as the fraction of carbon in the fuel divided by the fuel heating value. The result is expressed in kg CO_2/Joule or lb CO_2/Btu.

where EC is the emissions cost in mills/kWh, κ is the emissions coefficient for CO_2 emissions in kg/kWh, and P_{CO2} is the price of the carbon dioxide emissions in \$/ton CO_2. Since the reference plants emit more CO_2, their emissions costs will be higher. The emissions costs of the reference and capture plants are presented below in equation form. The emissions coefficients come from Table 2.

Reference plants:

$$EC_{gas\ ref} = 0.37 \times P_{CO2}$$

$$EC_{coal\ ref} = 0.74 \times P_{CO2}$$

Capture plants:

$$EC_{gas\ cap} = 0.04 \times P_{CO2}$$

$$EC_{coal\ cap} = 0.09 \times P_{CO2}$$

2.3.5 Total Costs

The total costs for the CCS technologies are presented in equation and graphical form. The following equations describe the total costs as a combination of the busbar, sequestration, transmission and distribution (T&D), and emissions costs. In this partial equilibrium analysis, the busbar, sequestration and T&D costs are constant, while the emissions costs depend on the carbon price; therefore, for simplification one can aggregate the costs into emissions costs and the total costs net of emissions. The following equations, generalized as Equation 1, present the total costs for the capture plants analyzed in this thesis and the reference plants on which they are based:

$$TotalCost = Busbar + Sequestration + Transmission \,\&\, Distribution + Emissions$$

$$= Total\ Cost\ Net\ of\ Emissions + Emissions\ Costs$$

Reference plants:

$$TC_{gas\ ref} = 32 + 0.0 + 20 + (0.37 \times P_{CO2}) = 52.0 + (0.37 \times P_{CO2})$$

$$TC_{coal\ ref} = 46 + 0.0 + 20 + (0.74 \times P_{CO2}) = 66.0 + (0.74 \times P_{CO2})$$

Capture plants: (1)

$$TC_{gas\ cap} = 53 + 3.6 + 20 + (0.04 \times P_{CO2}) = 76.6 + (0.04 \times P_{CO2})$$

$$TC_{coal\ cap} = 59 + 8.1 + 20 + (0.09 \times P_{CO2}) = 87.1 + (0.09 \times P_{CO2})$$

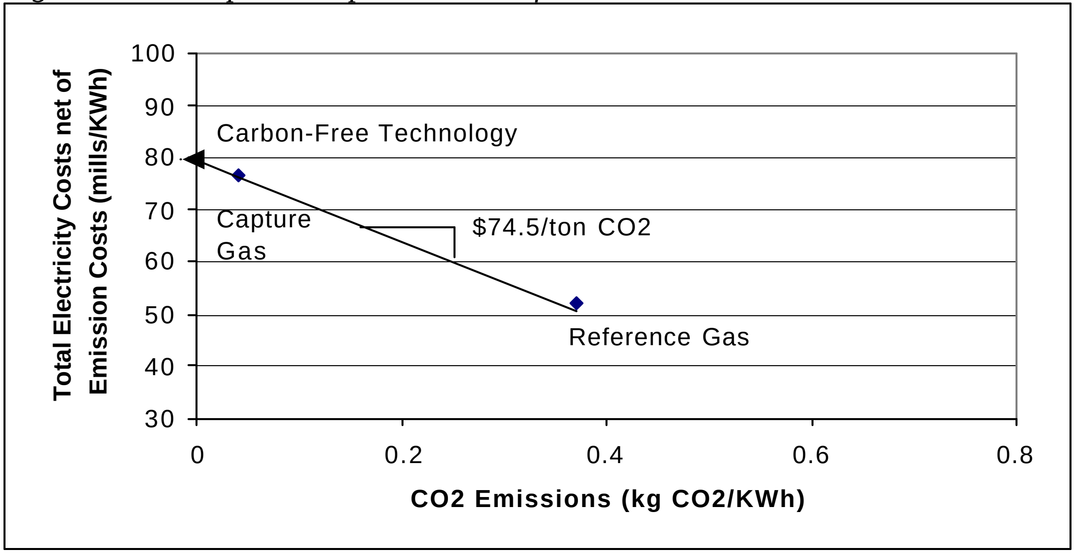
In this partial equilibrium framework, a technology's competitiveness is determined by its total cost. In a world where the carbon price is zero the capture plants would never be economic; however, carbon constraints as discussed in connection with global change policy measures would place a positive price on CO_2. A high enough carbon price would make the capture plants competitive. To determine the carbon price needed for a technology to be competitive, a calculation can be performed simply by comparing two plants and determining the carbon price at which the total costs are equal. Algebraically, the comparison appears as:

$$P_{CO2} = \frac{(TC^{*\prime} - TC^{*})}{(k - k')} = \frac{\$}{ton\, CO_2} \qquad (2)$$

where TC* is the total costs net of emission costs in mills/kWh, κ is the emission coefficient, and the prime (') identifies the cleaner, more expensive technology. For example, the reference gas technology can be compared to the gas capture technology by calculating a break-even carbon price of \$74.5/ton CO_2, which is equivalent to \$273/ton C.

One can represent this relationship graphically by placing the total costs net of emissions on the y-axis and the emission coefficient on the x-axis. Figure 1 plots the reference gas plant and the capture gas plant. The slope of the line connecting the two is simply the P_{CO2}, \$74.5/ton CO_2.

Figure 1. Graphical Representation of Abatement Cost/Carbon Tax



This graphical representation can be used to describe the cost competitiveness of all types of technologies. For example, the costs of a carbon-free (zero-emission) power technology can be compared to the two gas technologies by extending the line to the y-axis. One can solve for TC*' using Equation 2.

$$74.5 = \frac{(TC^{*\prime} - 52.0)}{(0.37 - 0.0)}$$

$$TC^{*\prime} = (74.5 \times (0.37 - 0.0)) + 52.0 = 79.6\ mills/kWh$$

If a carbon-free power technology costs more than 79.6 mills/kWh in a world with only the reference gas plant and the gas capture plant, the carbon-free technology would not be competitive. If the carbon price was higher than \$74.5/ton CO_2, the gas capture plant would be cheapest, and if the carbon price was lower, the reference gas plant would be cheapest.

2.4 Common Errors and Limitations

As stated previously, partial equilibrium analyses are very useful. They can assess technical feasibility, they can suggest areas where advancements can be made and they can estimate the costs of a technology on the project or microeconomic level. However, partial equilibrium models, like all models, have their limitations. The main limitation is that they cannot take into account changing prices. Today, we live in a world that poses few limits on our use of carbon. If we seek to understand which technologies will be competitive in a carbon-constrained world, we should evaluate the technologies at the prices in such a scenario. The divergence between the prices in the two scenarios can be great. First, as economic actors seek to reduce carbon emissions, they are bound to switch to use gas. The fuel switch increases the demand for gas and reduces the demand for coal. Furthermore, gas resources are generally believed to be smaller than coal; therefore, more price pressure will be placed on gas than coal from resource scarcity.

In addition to the limitations of partial equilibrium analyses, several errors can be committed when one either presents or interprets results of partial equilibrium analyses. These errors can be categorized into two principle types of errors: A) misrepresenting the total costs of the technology, B) misrepresenting the relative economics of the technology.

2.4.1 Type A Error: Misrepresenting the total costs of the technology

The costs of a technology can be presented in many ways, some more accurate than others. A couple options include presenting the costs in terms of total, variable, and marginal; or in capital, operations and maintenance, and fuel; or as I have in terms of busbar, electricity transmission and distribution, sequestration, and emissions. Whichever one chooses, one should be as accurate as possible and present all costs that will be a factor in choosing a technology.

The total costs of a technology can be misrepresented by inaccurately *measuring* the costs or *not including all costs* that are relevant to the usage of a technology. For example, the costs of a photovoltaic cell can be stated in terms of its initial capital investment alone. If one neglects the maintenance costs required by the owner to clean the surface then the costs have been inaccurately represented.

Such problems can also arise in *presenting* the costs of carbon capture and sequestration technologies. As described earlier, the busbar, electricity transmission and distribution, sequestration, and emissions costs are all important to the economics of the CCS technologies. Although most analyses understand the need to consider all costs, it is not too uncommon to lose perspective and focus only on one aspect of the costs. For example, one can state that a carbon capture power plant costs 50% more than a power plant capture technology. When this is a 50% increase in the busbar costs, it is incorrect to construe that the total costs are 50% more expensive. All costs are important. One must not forget that coal plants must sequester more carbon dioxide per kWh and that capture plants will still need to pay for their emissions costs. Lastly, electricity transmission and distribution costs can be important also, especially when plants are built in areas not connected to a grid.

In this chapter, I sought to accurately present all relevant costs of the CCS technologies and describe them on a common basis of mills/kWh. By doing so, I hope to avoid many problems that I believe are common in presenting the partial equilibrium costs of the CCS technologies.

2.4.2 *Type B Error: Misrepresenting the relative economics of the technology*[7]

Economic analyses of CCS technologies often do not compare the capture technology against the next best option. For example, when describing the relative economics of a coal capture plant, the costs can be expressed in terms of its incremental costs in mills/kWh or \$/ton CO_2. Herzog's analysis shows that the costs of a capture technology as expressed by the abatement cost in mills/kWh or \$/ton CO_2 depend highly on the reference plant that the capture plant is compared to. I use Equation 2 to show the Type B Error when comparing the coal capture plant to the coal reference plant. The difference in total costs net of emissions between the two options in mills/kWh is 21.1 and the \$/ton CO_2 is

$$P_{CO2} = \frac{(87.1 - 66.0)}{(0.74 - 0.09)} = 47.8 \frac{\$}{ton\, CO_2}$$

However, to calculate the true abatement costs of the coal capture plant requires comparing it to the true alternative, a gas plant. When one correctly compares the coal capture plant to the reference gas plant one receives a higher incremental cost and a much higher cost of abatement.

$$P_{CO2} = \frac{(87.1 - 52.0)}{(0.37 - 0.09)} = 161 \frac{\$}{ton\, CO_2}$$

Nonetheless, the partial equilibrium framework is a very important tool and it can be used to understand the economics of the CCS technologies. Modeling CCS technologies will help to clarify how the economics change in a dynamic world where prices are not constant.

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[7] Herzog pointed to the Type B Error in "The Economics of CO_2 Separation and Capture" (1999).

3 Modeling Carbon Capture and Sequestration Technologies

This thesis utilizes the MIT Emissions Prediction and Policy Analysis (EPPA) model (Babiker *et al.,* forthcoming). The EPPA model is a recursive dynamic multi-regional general equilibrium model of the world economy which has been developed for analysis of climate change policy. EPPA owes much of its structure to the original GeneRal Equilibrium EnviroNmental (GREEN) model, which was developed by the OECD (Burniaux *et al*., 1992). EPPA modelers have modified the original GREEN version and are constantly improving its functionality. Since the spring of 1999 modelers have been using version 3.0. This current version of the model is built on a comprehensive energy-economy data set (GTAP-E[8]) that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows. The base year for the model is 1995 and it is solved recursively at 5-year intervals. EPPA consists of 12 regions, shown in Table 3, which are linked by international trade; 9 production sectors; and 1 representative consumer for each region. This thesis focuses mainly on the USA region and the electricity sector.

3.1.1 Functional Form

Constant elasticity of substitution (CES) functions are used to describe the nature of production and consumption within each region and sector. In each time step the model solves these functions for a set of prices that clears supply and demand across regions and sectors. They describe mathematically how the factors of production can be combined to produce output, and how consumers trade off among goods to maximize utility. Different technologies are represented by production functions that use inputs in different combinations to produce their respective goods.

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[8] This special database is provided by the Global Trade Analysis Project (GTAP) along with release four of their economy-trade database. For further information on GTAP see Hertel (1997).

Table 3. EPPA Regions and Sectors

Country or Region		Sectors	
Annex B	*Name*	*Production*	*Name*
United States	**USA**	Agriculture	**AGRIC**
Europe	**EEC**	Coal	**COAL**
Japan	**JPN**	Oil	**OIL**
Other OECD	**OOE**	Gas	**GAS**
Former Soviet Union	**FSU**	Petroleum	**REFOIL**
Eastern Europe	**EET**	Energy Intensive	**ENERINT**
Non-Annex B		Other Industries	**OTHERIND**
Dynamic Asian Economies	**DAE**	Electricity	**ELEC**
		Investment	**INV**
Brazil	**BRA**	Factors of Production	
China	**CHN**	Capital	**K**
India	**IND**	Labor	**L**
Energy Exporting Countries	**EEX**	Fixed Factor	**FF**
Rest of World	**ROW**		

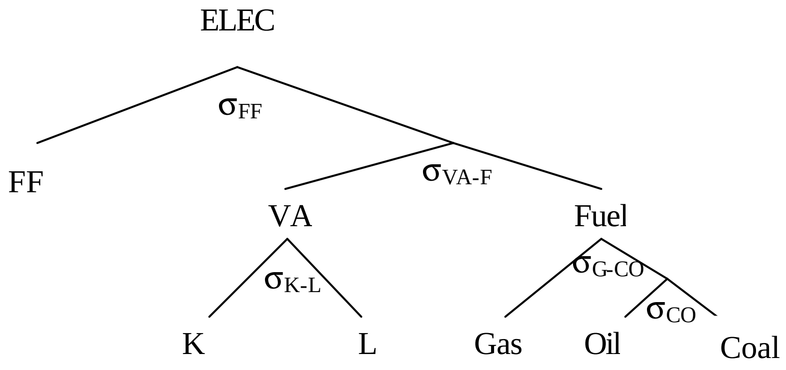
The functions within EPPA are predominantly CES production functions, which look like:

$$CES: \quad Y_i = \left[a_1 X_1{}^r + \ldots a_n X_n{}^r \right]^{1/r}$$

The term constant elasticity of substitution indicates that the substitutability among all inputs, X_n, does not vary with quantity levels and/or prices. The elasticity of substitution, σ, where $\rho=(1-\sigma)/\sigma$, determines how fungible the inputs are. The factor shares, a_n, represent the relevant amounts of each input required to produce the output, Y_i.

Each input, X_n, can itself be the output of a lower-level production function. The basic factors of production produce intermediate goods, which combine with other goods, both intermediate and basic factors of production, to produce final goods. This hierarchical production structure is called nesting. Graphically, tree diagrams are used to represent the nesting of production functions. The tree diagram of the electric sector in EPPA is provided in Figure 2. In the electricity sector value added (VA) is produced by optimizing the combination of capital and labor based on their respective prices; gas, oil, and coal similarly combine to produce a fuel aggregate; then value added and fuel are aggregated before a top-level nest combines the fixed factor with the value added and fuel bundle. Each nesting of production functions is solved simultaneously in the model to maximize output across regions and sectors.

Figure 2. Conventional Electricity Tree Diagram



3.1.2 Parameterization of the Production Functions

The parameters of the production functions are determined by the modeler with the aid of a balanced social accounting matrix (SAM). A SAM is a data set that includes all the economic flows in and out of regions and sectors. The SAM used by EPPA is compiled by aggregating variables given by the GTAP-E database (Hertel, 1997). The actual values for the input and output variables are the input and output variables in the social accounting matrix. The modeler determines the nesting of these variables and the elasticity of substitutions so that they best represent the nature of the economy. The EPPA model is a computable general equilibrium model, representing the entire world economy. This broad coverage means, however, that details on individual sectors and technologies are limited so that the model remains computationally feasible. Still, models must focus on the relationships that are critical to the problem being addressed. EPPA, designed to analyze restrictions on carbon dioxide emissions, has a structure that focuses more on energy production and use. Based on the information from the SAM, the production nesting, and the elasticity of substitutions, the model compiler solves the base year. Succeeding time steps are solved based on current year values and is driven by assumptions about labor productivity, fixed factor supplies, and exogenous improvement in energy efficiency.

3.2 The Electricity Sector in EPPA

The current electricity structure contains discrete production functions for nuclear and conventional electricity as well as a non-carbon backstop[9]. The new carbon capture and sequestration technologies will be discrete production technologies that compete directly with these other electricity production options. In the reference model, nuclear output remains fairly constant under almost all policy scenarios and the non-carbon backstop is not used; therefore, a new technology would have to compete primarily with the conventional electricity sector and thus I will concentrate on describing this nesting.

The conventional electricity sector is comprised of a production nest that is represented by the tree structure in Figure 2 and by the parameters in Tables 4 and 5 for the USA region. The values in Table 4 represent the total expenditures involved in producing the electricity for the end consumer. Electricity transmission and distribution costs are not explicitly accounted for in the data, nor are expenses for individual plants. The data is an aggregation of all of the costs to produce and transmit electricity.

The economics of production in the electricity sector focuses on multi-sector market interactions and trade effects. This is consistent with the top-down nature of the model. All non-nuclear electricity generation is represented without individual technologies or their market shares explicitly represented. Instead, the amount of capital, labor, coal, gas, oil, and fixed factor used by the electricity sector indicates the extent to which individual technologies are being used. The economics of technology choice is represented by the mathematics governing the substitutability among inputs. For example, the economics of switching production from gas to coal power is embedded in the production function's ability to substitute gas from oil and coal.

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[9] For an explanation of how previous backstops were implemented into the model, see Kendall, (1998).

Table 4. Data for USA Conventional Electricity Sector

Data from GTAP*			
Variable	Description	Value (10^{10} US$)	Share of Total
ELEC	Total Electricity Spending at Point of Sale	18.8	1.0
K	Rents from capital by the electricity sector	11.8	0.62
L	Payments to labor by the electricity sector	3.88	0.21
OIL	Payments to oil purchased by the electricity sector	0.29	0.02
COAL	Payments to coal purchased by the electricity sector	2.55	0.14
GAS	Payments to gas purchased by the electricity sector	1.00	0.05
Calculated Data**			
Price of Electricity	66.1 mills/kWh		
CO_2 Emissions	0.72 kg CO_2/kWh		

[*] Values are for total non-nuclear spending in the United States, i.e. GTAP totals net nuclear expenditures. Totals represent the amount paid at the point of sale and include spending for transmission and distribution.

[**] Values are calculated using GTAP data and data from the Energy Information Agency (EIA). See Appendix for calculations.

Table 5. Elasticity of Substitutions in Electricity Sector

Parameter	Description	Value
$\sigma_{K\text{-}L}$	Capital vs. Labor	1.0
$\sigma_{VA\text{-}E}$	Value Added vs. Energy Bundle	0.4
σ_{FF}	Top-level Fixed Factor	0.6
σ_{CO}	Coal vs. Oil	0.3
$\sigma_{G\text{-}CO}$	Gas vs. Coal-Oil Bundle	1.0

In the 1995 base year in the United States, the relative amounts of inputs reflect the amount of production from various power sources. Because power from coal represents 52% of total electricity production in the United States (IEA, 1996), the relative amounts of inputs in the base year SAM reflect fairly closely that of a typical coal plant. A typical coal plant will cost 4.6 cents/kWh and pay 2 cents for transportation and distribution (Herzog, 1999)—almost identical to EPPA's 66.1 mills/kWh. Of the 4.6 cents for a coal plant, 3.0 are capital costs, 1.0 are coal costs, and 0.6 are labor costs—

also similar proportions to EPPA. Also, emissions in EPPA, 0.72 kg CO_2/kWh for conventional electricity in the USA in the base period, are also comparable to the emissions from coal plants of 0.74 to 0.77 kg CO_2/kWh, as found by Herzog (1999).

In the future we expect that power will be produced by a different mix of technologies, and inputs will be used more efficiently to produce a unit of output. The model takes these expectations into account, and the relative amount of inputs producing electricity change over time in the model. The Autonomous Energy Efficiency Improvement (AEEI) exogenously improves the efficiency of fuel use to produce a unit of output. As a result, the electricity sector becomes more efficient by being able to produce more electricity with less fuel. Also, as input prices change, the electricity generation will switch away from expensive inputs to less expensive inputs. For example, if coal becomes expensive and gas becomes cheaper, production will switch from coal to gas. If all fuels become expensive, production will switch away from fossil fuels and more towards production from capital and labor, thus representing a switch towards increased efficiency or possibly renewables. However, the marginal cost of increased electricity production in EPPA is not the marginal cost of a specific technology, instead it is the marginal cost of the aggregate production function.

One could also model the electricity sector with a more disaggregated or bottom-up approach. Such an implementation would clearly indicate which technologies are being used instead of relying on the relative proportions of the inputs to determine the usage of different technologies. This implementation of CCS technologies is an example of such an approach, as are the representations of nuclear power and the non-carbon backstop. The following section will describe the process required to implement such discrete technologies.

3.3 Implementation of CCS technologies

To implement the CCS technologies in the EPPA model, a set of production functions must be developed that correctly describes the economics of the technologies. One must choose the form of the function, the inputs, the share coefficients, the elasticity of substitutions, and the nature in which it interacts with the rest of the model. Whereas the current structure of the model was determined with the help of the GTAP database, the CCS technologies were not used widely enough in the 1995 base year to be identified separately in the GTAP database; therefore, the CCS technologies are implemented with the aid of engineering data. The new technologies will be discrete production functions that describe specific technologies. To keep the implementation simple, I will introduce the technologies in the USA region only. The parameterization of the production functions will determine how the technologies compete with other power options. Electricity produced by each power technology (conventional, nuclear, and CCS) is assumed to be a homogenous good.

3.3.1 Structure

The form or structure of the production functions determines how the inputs combine to produce electricity from the CCS technologies. I implement two separate production functions, one for the coal capture technology and one for the gas capture technology. Figure 3 represents the structure of the coal capture technology. The gas capture technology has the same structure, except with gas as its fuel input. The CES structure for the CCS technologies is fairly similar to conventional electricity because it combines fixed factor, value added, and fuel at the top level (compare Figures 2 and 3). However, differences occur because the CCS implementation is a discrete technology and the inputs must correspond with the engineering data in the base year, whereas the conventional electricity corresponds with the GTAP database. One such difference arises with the consideration of electricity transmission and distribution costs. In conventional electricity, electricity transmission and distribution costs are implicitly included in the conventional electricity structure, whereas the CCS structure explicitly incorporates electricity T&D within the fixed factor bundle. With this representation, the value added and fuel bundles of the CCS technology represent the busbar, emission, and sequestration costs and the fixed factor bundle incorporates the electricity T&D costs. Since transmission of electricity to the end consumer is hard to substitute for, the elasticity of substitution is set to zero (see Table 7).

Other differences arise with the incorporation of the sequestration process. Sequestration is placed in the fuel bundle to allow for correct accounting of the carbon emissions. Emissions costs are normally included in the fuel costs; therefore, the fuel

Figure 3. Tree Diagram for new CCS Technologies (Coal Example)

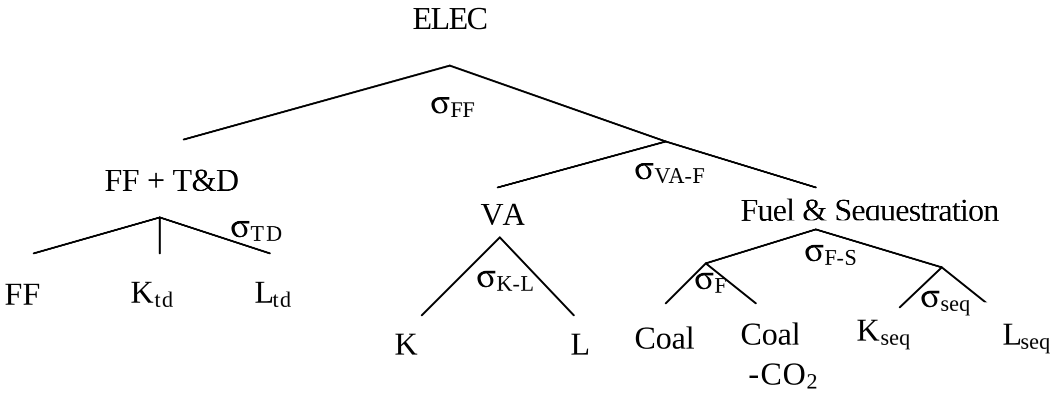

Table 6. Elasticity of Substitutions in CCS production functions

Parameter	Description	Value
σ_{FF}	Top-level substitutability for the Fixed Factor and T&D	0
σ_{TD}	Top-level substitutability between the Fixed Factor and T&D	0
σ_{VA_F}	Ability to substitute between the value added and fuel inputs.	0.4
σ_{K_L}	Ability to substitute between capital and labor in producing the value added.	1.0
σ_{seq}	Ability to substitute capital for labor in disposing of the captured CO_2	0.2
σ_{F-S}	Ability to substitute between fuel and sequestration costs.	0
σ_F	Ability to change the proportional amount of carbon that is captured from the fuel.	0

costs are normally the fuel costs plus the carbon emissions costs. To take account of the decreased emissions resulting from the capture process, the emissions costs must be subtracted from some of the fuel; therefore, in Figure 3 there is an input of coal with CO_2 and one without CO_2 (Coal – CO_2). To ensure that sequestration costs are incurred for each subtracted ton of carbon, the costs of sequestration are placed at the same level as the fuel and emission costs. The elasticity of substitution between the sequestration bundle and the fuel and emissions bundle, $\sigma_{F-S,}$ is zero to represent the idea that for each ton of carbon subtracted from the fuel, the costs of sequestering one ton must be incurred. The ability to substitute among inputs is determined by the substitution parameters in Table 7. With the exception of the parameters previously mentioned, the parameters were chosen with judgment from experience with the model and the values of the parameters in conventional electricity.

3.3.2 Total Costs and Implementation via Sum of the Factor Shares

The total costs of the CCS technologies are specified under the base year prices by choosing the sum of the factor shares in the base period. The sum of the factor shares multiplied by the factor prices determines the total costs, and the shares themselves represent the proportional amount of each input. By definition, for conventional electricity the sum of factor shares is 1.0 in the base year. Of this total, Table 4 sets out the proportions. For example, 0.62 in the table indicates that $0.62 of every dollar goes to capital. For the CCS technologies, determining the proportional costs of the inputs is fairly easy, because the engineering data provide a basis for determining how much of the total cost comes from fuel, capital, and labor. However, determining the total cost in terms of the sum of factor shares is more troublesome.

There are several possible ways to parameterize the total cost of the CCS technologies. Earlier, I showed that average electricity prices in 1995 were 66.1 mills/kWh in the United States and the sum of factor shares for conventional electricity is 1.0 in the base year. Because CCS technologies cost more than conventional sources of electricity in the base period, the sum of factor shares needs to be greater than 1.0 in the base period. If one were to specify the sum of factor shares for a CCS technology to be 1.5, then it would be 50% more expensive than conventional electricity and cost about 1.5 x 66.1= 99.2 mills/kWh. Using this rationale and the parameters for the capture plants from Equation 1, a choice for the sum of factor shares would be 76.6/66.1 = 1.16 and 87.1/66.1 = 1.32 for the gas and coal capture technologies, respectively.

However, as a result of this choice of factor shares the CCS technologies will enter at carbon prices that are too low. This happens because the relative economics depend highly on what the capture technologies are being compared to. Here, conventional electricity is the technology to which the capture technologies are being compared. The costs of the conventional electricity are the average of many technologies and are not equivalent to the marginal costs representative of a modern day NGCC plant; therefore, the parameterization of the factor shares will require more thought.

The partial equilibrium framework described by Equations 1 and 2 can be used to gain intuition as to why this option for the sum of factor shares (1.16 for the gas capture and 1.32 for the coal capture technology) causes the CCS technologies to enter at too low of a carbon price. To utilize these equations, the total costs net of emissions, TC*, and the emission coefficients, κ, for the capture technologies and conventional electricity must be determined as they are represented in the model. The total cost net of emissions is determined by multiplying the sum of factor shares by the price of electricity. The emission costs are determined by multiplying the emission coefficient by the carbon price. The calculations for the capture technologies and conventional electricity are presented below in Equation 1 form:

$$TC_{Conv.Elec.} = 1.0(66.1) + (0.72 \times P_{CO2})$$

$$TC_{CoalCapture} = 1.32(66.1) + (0.09 \times P_{CO2})$$

$$TC_{GasCapture} = 1.16(66.1) + (0.04 \times P_{CO2})$$

where the price of electricity in the base period as well as the emission coefficient for conventional electricity are taken from Table 4. The parameters for the capture technologies are taken from the above assumption of the sum of factor shares and the emission coefficients of Table 2. By setting $TC_{Conv.Elec.} = TC_{CoalCapture}$ and $TC_{Conv.Elec.} = TC_{GasCapture}$ one can calculate the carbon price in \$/ton CO_2 required for the CCS technologies to be competitive if the total costs net of emissions, TC*, and the emission coefficients, κ, do not change from the base period.

$$P_{CO2 \quad gas\,capture} = \frac{\left(1.16(66.1) - 1.0(66.1)\right)}{(0.72 - 0.04)} = 15.6 \frac{\$}{T \ CO_2}$$

$$P_{CO2 \quad coal\,capture} = \frac{\left(1.32(66.1) - 1.0(66.1)\right)}{(0.72 - 0.09)} = 33.6 \frac{\$}{T \ CO_2}$$

Engineering data shows that a gas capture plant will not be competitive until carbon prices reach \$74.5/t CO_2. The discrepancy arises because the capture plants in this instance are competing against EPPA's conventional electricity sector, which has higher costs and higher emissions than the base NGCC plant considered in the partial equilibrium analysis. A more accurate implementation of the costs of the CCS technologies would have a smaller drop in the emissions (the denominator in Equation 2) and a larger increase in the total costs net of emissions (the numerator in Equation 2) than that shown above. Since the conventional electricity sector is not being changed in this thesis, and the emissions of the CCS technologies are already low, one way to ensure that the CCS technologies enter at appropriate carbon prices is to increase the sum of the factor shares of the CCS technologies.

An increase as described in Table 7 by the TOD option (Today's Technology, named for reasons explained later) represents the relative economics best in the short term and Equation 2 can explain why. First, it must be explained that the total costs net of emissions and the emissions of the conventional electricity sector change over time from the base period where TC*=66.1 and κ=0.72. This happens because carbon constraints provide an incentive to substitute inputs such as value added for fuel and gas for coal. Furthermore, less fuel per unit of output is used as a result of the AEEI. For policy cases of interest, TC* moves from 66.1 in the base period and stays in the range of 67.0 to 71.0 between 2015 and 2035. Conventional electricity's emissions, κ, move from 0.72 in the base period and remains in the range of 0.48 to 0.56 between 2015 and 2035. The more stringent the carbon constraints, the more incentive conventional electricity has to switch inputs and reduce emissions; therefore, the costs will be higher and the emissions will be lower. Conversely, when carbon constraints are less stringent, the costs

Table 7. Factor Shares for 3 Implementation Options

	LTI (Lg. Tech. Improvements)		STI (Sm. Tech. Improvements)		TOD (Today's Technology)	
	Gas	Coal	Gas	Coal	Gas	Coal
Total Cost in Factor Share	1.16	1.32	1.37	1.53	1.51	1.71

of conventional electricity will be lower and emissions will be higher. Therefore, the parameters for TC* and κ to use in Equation 2 for conventional electricity can be estimated by the costs and emissions that are most likely under the policy cases of interest: TC*=69.0 and κ=0.52. When conventional electricity has these costs and emissions, the gas capture technology is competitive at approximately \$73/t CO_2 with the TOD parameterization.

$$P_{CO2 \quad gas\,capture} = \frac{(1.51(69.0) - 69.0))}{(0.52 - 0.04)} = 73 \frac{\$}{T \ CO_2}$$

The TOD parameterization represents the costs of today's CCS technologies. However, many believe that CCS technologies could become less expensive through technological advances. Herzog (1999) states that advances in the CCS technologies could advance more rapidly over time than advances in power plants without carbon capture technologies. In the future the gas and coal capture technologies could cost 45 and 50 mills/kWh busbar, respectively by 2012, instead of 52 and 59 mills/kWh busbar today. Because of model constraints, this concept of technological change where breakthroughs are made over time is difficult to represent. Instead the concept of different rates and degrees of technological improvements has to be accounted for in the specification of the sum of factor shares for CCS in the base year. The STI option (short for Small Technological Innovation) provides an approximation of the costs of the CCS technologies under the technological advances described above. Using the same method as above, the gas capture technology becomes competitive at approximately \$53/t CO_2 with a STI parameterization.

$$P_{CO2\ \ gas\,capture} = \frac{(1.37(69.0) - 69.0))}{(0.52 - 0.04)} = 53\ \frac{\$}{T\ CO_2}$$

If one anticipates even larger technological advances, the first option where the gas and coal capture technologies has sum of factor shares of 1.16 and 1.32, respectively, can be considered. The sum of factor shares for this option, LTI (Large Technological Improvement), is detailed along with the sum of factor shares for the other options, TOD and STI, in Table 7. I choose to analyze the TOD scenario in the reference runs.

3.3.3 Control of the Rate and Level of Market Penetration

Without the use of some device to restrain the rate of penetration, the behavior of the CCS technology would not make economic sense within EPPA. The model solver chooses the electricity generation option with the lowest cost and once a CCS technology became the least-cost option, production would massively switch or "bang" over towards it. However, this is unlikely to happen in the real world. When a technology first becomes economic, its penetration may be limited by the number of engineers available to design new CCS plants and the time required to attain a permit to build a plant or to gain access to a sequestration sink. We represent these restrictions by introducing a fixed factor. The fixed factor is expressed as Leontief at the top level of the nesting (see Figure 3) and only a very small amount is needed to produce electricity. To control the entry and level of market penetration, the supply in each time period of the fixed factor is exogenously determined by the modeler. If there is an unlimited supply, the fixed factor is inexpensive and minimally affects CCS electricity production. If there is no supply, then the fixed factor is infinitely expensive and due to the Leontief representation, the CCS technology is also infinitely expensive. The correct representation lies somewhere in the middle.

The fixed factor supply is chosen to slow the penetration rate, but not the overall level of penetration. To slow the penetration rate, the supply is limited in the early periods of market entry. In the later time periods, the fixed factor supply is large and thus allows the CCS technologies to compete solely on price. One could adjust the fixed factor supply in the latter time periods if one believed the storage, permitting, political, or other rigidities to be larger. The potential sequestration capacity exists for any possible scenario evaluated in this exercise, but we do not know enough about the political feasibility, storage integrity, and environmental safety associated with the various storage options to know how much of the potential could be utilized. To the extent that market rigidities and permitting problems are minimal in the long term, and sequestration options exist for the carbon dioxide, the reference fixed factor supply should be appropriate for the model.

4 Scenarios and Results

The CCS technologies are analyzed under two policy scenarios, Kyoto and Stabilization (see Table 8). The scenarios are based on the Kyoto Protocol and the objectives of the United Nations Framework Convention on Climate Change (UNFCCC). The model results are compared to the business as usual (BAU) scenario and also against Kyoto and Stabilization scenarios without CCS technologies. The Kyoto scenario assumes that Annex B nations reduce to Kyoto commitment levels in 2010 and hold these emission levels until 2100. Non-Annex B nations continue to develop without carbon constraints. The Stabilization scenario assumes that all nations will eventually constrain emissions so that carbon concentrations in the atmosphere will be stabilized at 650 ppmv.[10] Annex B regions reduce to Kyoto commitment levels in 2010 and then reduce

Table 8. Policy Scenarios Analyzed

Scenario	*Description*
BAU	Business as Usual—No carbon constraints in any regions
Kyoto	All Annex B countries reduce to Kyoto constraints in 2010 and remain at these levels until 2100
Stabilization	Atmospheric carbon stabilized at 650 ppmv. All Annex B countries reduce to Kyoto constraints in 2010 and reduce by additional 5% in each subsequent 15-year period. All Non-Annex B countries reduce to 2010 levels in 2025 and reduce by additional 5% in each subsequent 15-year period.
Variations	
With Trading (T)	Carbon permits are tradable among Annex B regions
No Trading (NT)	Carbon permits cannot be traded among regions
With CCS	CCS technologies available
No CCS	CCS technologies not available

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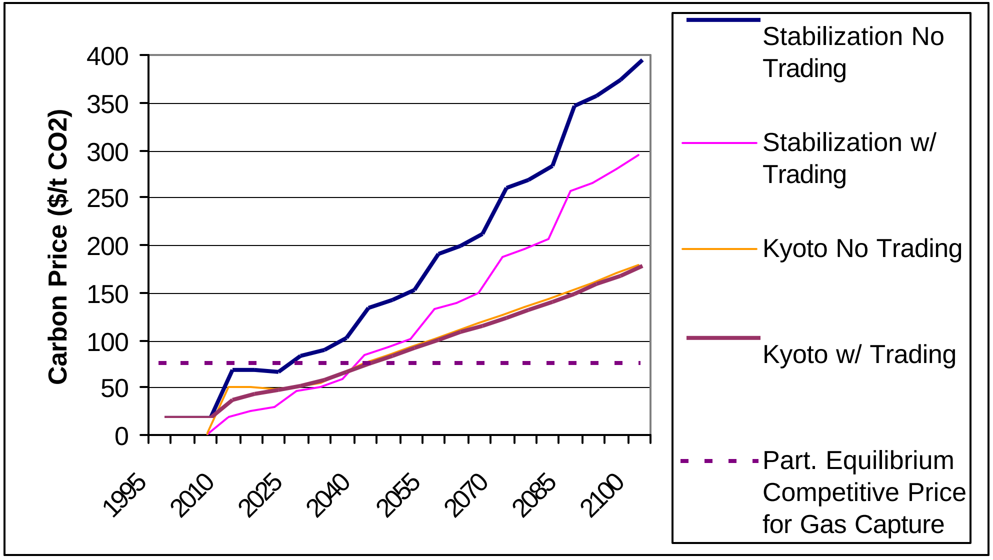
[10] This scenario is the same as used in Reilly et *al*, (1999).

by additional 5% increments in each succeeding 15-year time period. Non-Annex B regions reduce to 2010 levels in 2025 and also reduce by additional 5% increments in each succeeding 15-year time period. Two variations of each scenario are analyzed, one with an international tradable permit system that allows trade between Annex B regions and one without trade between regions. A scenario that allows global trade in permits is not analyzed. If such a global trading scheme were analyzed in the Stabilization scenario, the resulting carbon prices would be similar to those seen in the Kyoto scenarios analyzed in this thesis. If such a global trading scheme were analyzed in the Kyoto scenario, the resulting carbon prices would be lower than those seen under the Kyoto scenarios analyzed.

Under these scenarios the CCS technologies can become economically competitive in the United States. This is understandable given that the partial equilibrium analysis judges the gas capture technology to be competitive at carbon prices of $74.5/t CO_2 (see Chapter 2) and carbon prices in the United States will rise above $74.5/t CO_2 in the scenarios analyzed (see Figure 4). Figure 4 shows that carbon prices in the United States will increase monotonically over time and will break the $74.5/t CO_2 barrier in time periods between 2035 and 2075. The carbon prices range from $375/t CO_2 in 2100 in the Stabilization scenario without permit trading to $150/t CO_2 in 2100 in the Kyoto scenario with trading. Within this range the CCS technologies are competitive.

Figure 4. Carbon Prices in USA in Scenarios without CCS Availability

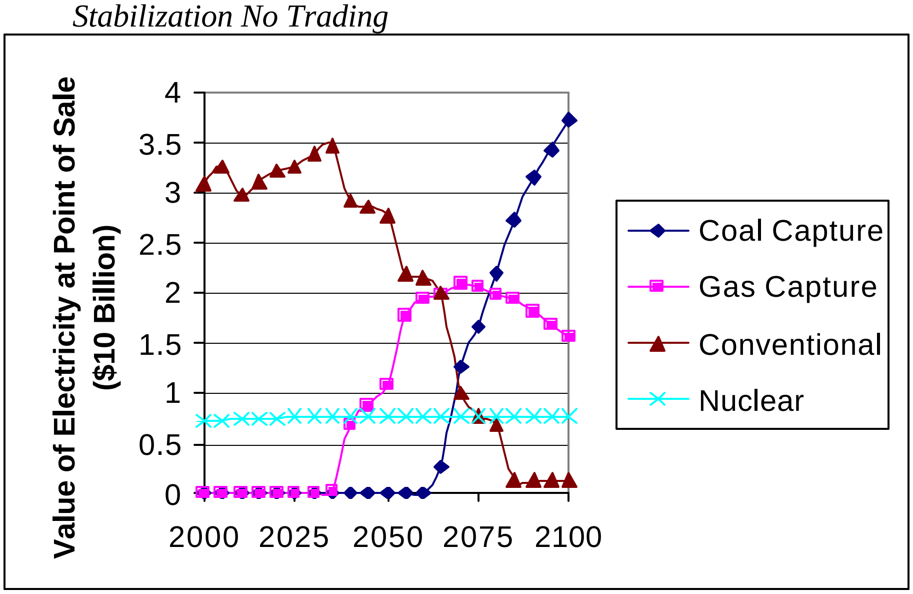


4.1 Analysis of Stabilization without Trading Scenario

To understand the results and their sensitivities I will first present the results of the Stabilization without trading scenario. Because Stabilization meets the goal of the UNFCCC, stabilization of the atmosphere, it provides a good long-term scenario to test the CCS technologies. Because I only introduce the CCS technologies in the United States, the inability to trade permits minimizes the trade effects that could ensue due to the increased ability of the United States to abate carbon at lower costs.

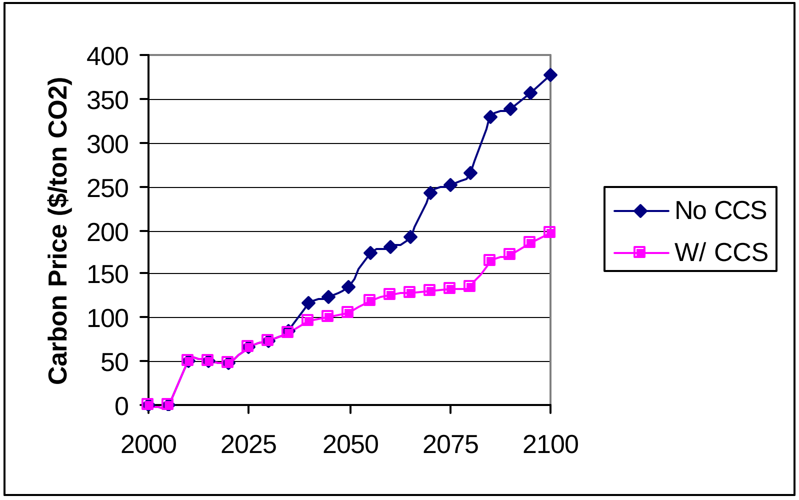
Figures 5 through 8 show the results from the Stabilization scenario in terms of the level of penetration of the CCS technologies into the electricity sector, the reduction in the carbon price, and the general equilibrium effects on fuel prices in the economy. As a result of the use of the coal and gas capture power generation options, 38 GtC are sequestered between 2035 and 2100 in the United States. Table 1 indicates that there is adequate storage capacity for this amount of captured carbon. However, because Table 1 represents *worldwide* estimates and because of the many types of uncertainties mentioned in Chapter 2, such an estimate suggests a need to ensure that adequate capacities are proven capable for use.

Figure 5. Value of Electricity Output from Different Sources in USA under Stabilization No Trading



In figure 5, one can notice dynamics of the two CCS technologies in the United States. The gas capture technology enters first in 2035 and captures almost 50% of the market by 2070. This huge demand for gas coupled with a low demand for coal eventually makes the coal capture technology more economical and the United States experiences a massive switch over to the coal capture technology in 2070. One can notice that the CCS technologies dominate the US electricity sector in the latter half of the century. Figure 6 shows that this reduces the carbon price significantly, but does not stop the carbon price from increasing. The carbon price must increase due to the persistent need to reduce in other sectors. Because the electricity sector becomes a cheaper reduction option, much of the abatement switches over to the electricity sector.

Figure 6. Carbon Price in USA under Stabilization No Trading



An important explanation for the relative changes in the coal and gas prices change over time—Figures 7 and 8. In the business as usual (BAU) scenario with no carbon constraint, gas and coal prices increase monotonically over time. Gas prices increase more than ten fold whereas coal prices increase a little more than two fold. In the Stabilization scenario, the demand for both fuels is greatly diminished when the CCS technologies are not available. When the capture technologies are available, however, the demands for the fuels increase, as does the price. One can notice that the increases in gas and coal prices are correlated with the use of the respective capture technologies. Furthermore, one can notice that the changes in fuel prices affect the competitiveness of the capture technologies.

Figure 7. *Gas Prices in USA under Stabilization No Trading and BAU*

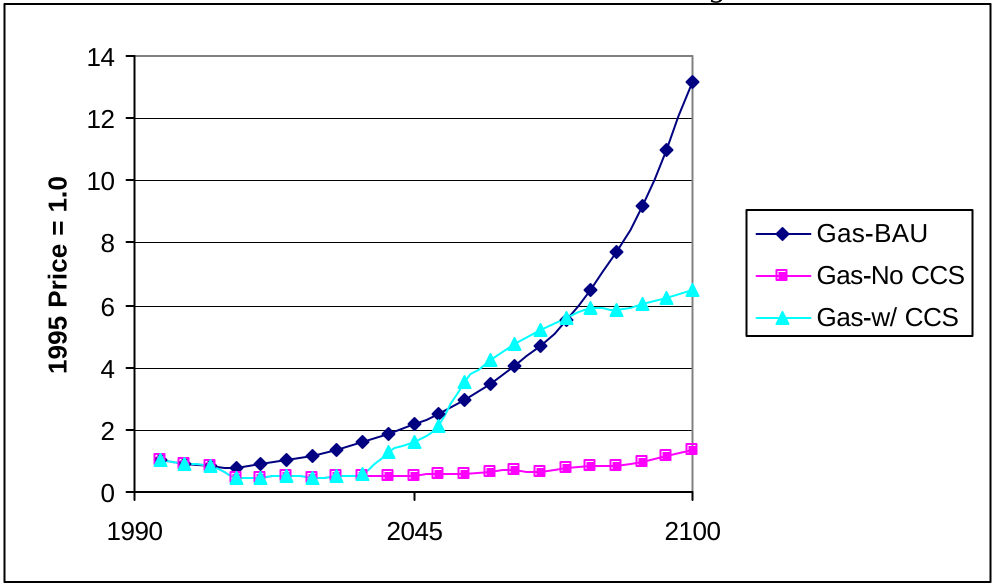
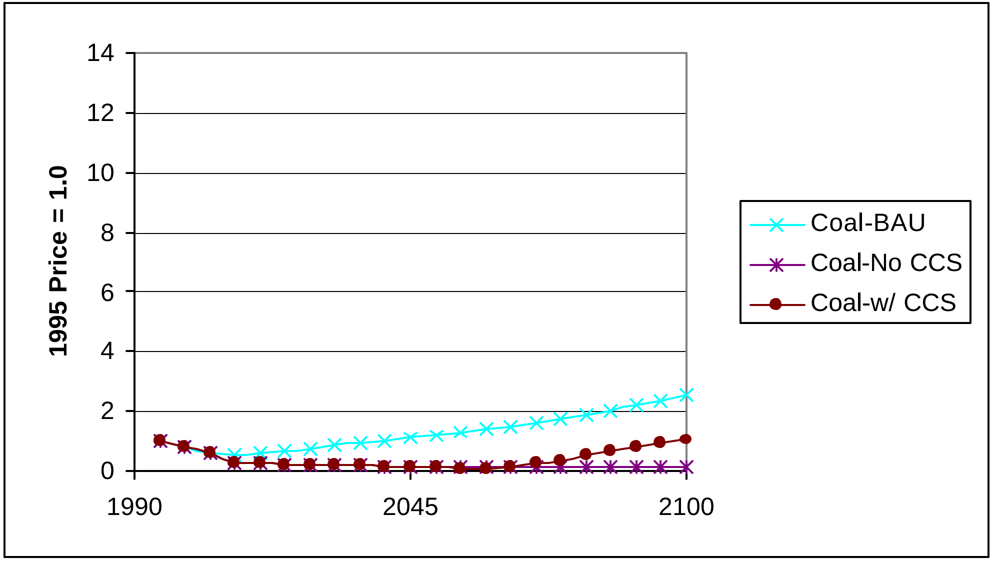


Figure 8. *Coal Prices in USA under Stabilization No Trading and BAU*



Before the CCS technologies enter the market other reduction measures are undertaken. The electricity sector switches from coal to gas and improves efficiency and consumers decrease their demand for electricity and other energy services. When emission constraints become more and more stringent and the carbon price increases, these reduction measures are supplemented by the adaptation of the CCS technologies.

Other effects in the economy should also be noted. As a result of using the CCS technologies, GDP expands at a slightly greater rate, welfare is increased in the United

States in 2100 by 1%, and output from other sectors of the economy expand compared with the Stabilization case where the CCS technologies are not available.

4.2 Analysis of other Policy Scenarios

The Stabilization scenario without trading is the most stringent scenario analyzed here, and the CCS technologies realize relatively large market shares in this scenario. In other less stringent scenarios, the CCS technologies penetrate into the market in later time periods and gain less of a market share. Figures 9 through 11 show the level of penetration of the CCS technologies under other policy options. The results of the Stabilization with trading scenario are very similar to the Stabilization without trading scenario. The gas and coal technologies enter 5 years later with trading, but realize similar penetration rates and levels (see Figure 9). The CCS technologies are less competitive in the Kyoto scenarios both with and without trading. Figures 10 and 11 show that the CCS technologies enter in later time periods and realize lower penetration levels.

Figure 9. Value of Electricity Output from Different Sources in USA under Stabilization with Trading

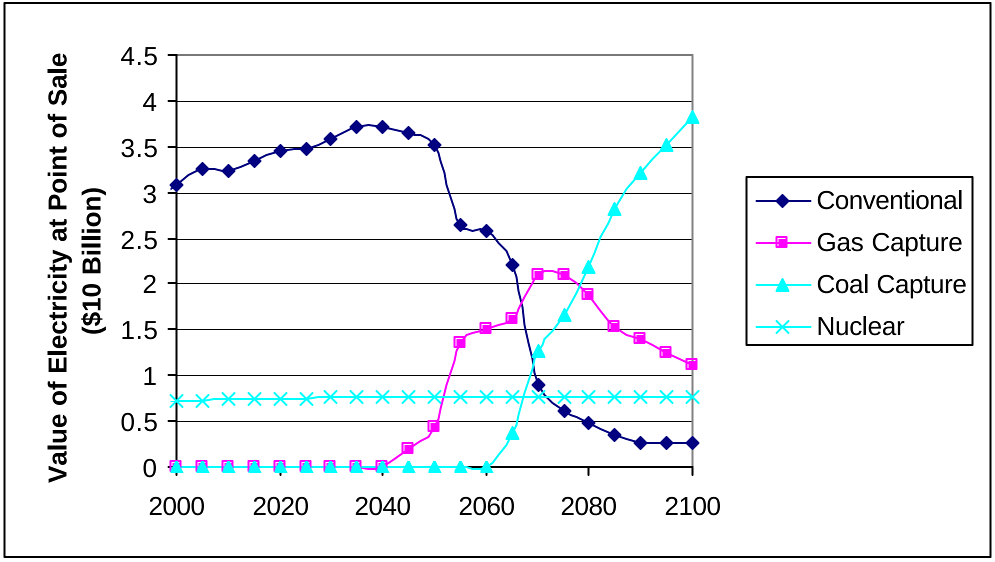


Figure 10. Value of Electricity Output from Different Sources in USA under Kyoto No Trading

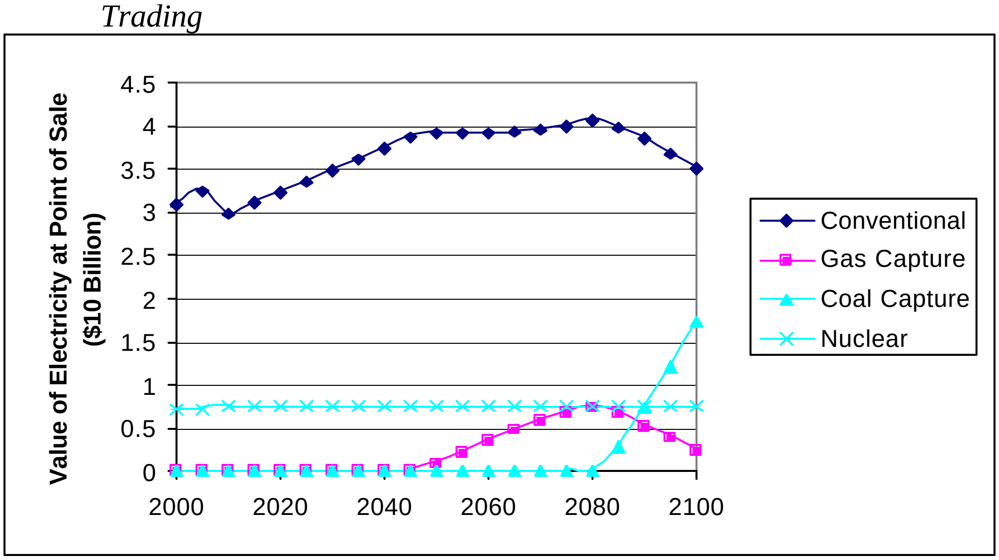
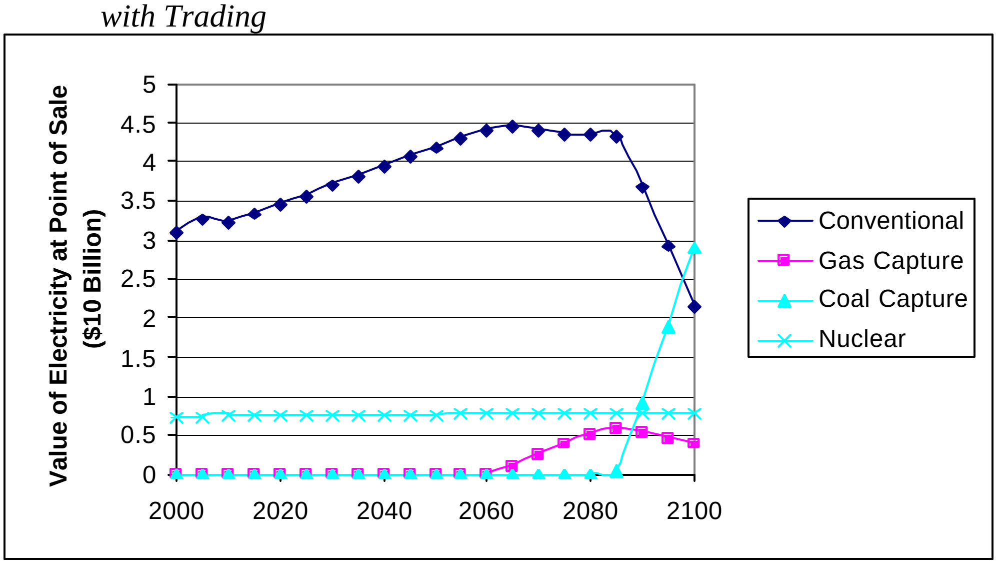


Figure 11. Value of Electricity Output from Different Sources in USA under Kyoto with Trading

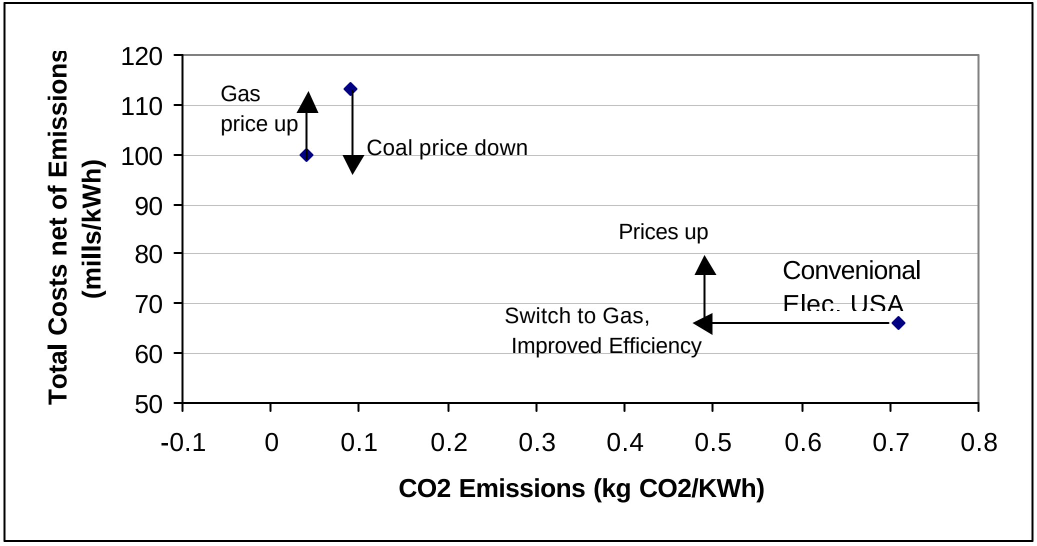


4.3 Understanding the Results

To understand the results, the partial equilibrium framework in Chapter 2 can be expanded to understand exactly how the technologies behave in the general equilibrium framework of EPPA. As described in Equation 2, the economic competitiveness of the CCS technologies is determined by the carbon price (P_{CO2}) and the relative total costs of the competing technologies in terms of the total costs net of emissions (TC') and the emissions (?). The CCS technologies must compete predominantly against conventional electricity in the United States. As prices change and as the conventional electricity sector evolves, these parameters—P_{CO2}, TC', and ?—change. Figure 12 shows how these parameters can change over time. Figure 12 is similar to Figure 1, but Figure 12 shows the CCS technologies compared with conventional electricity as parameterized in the model.

If the prices in the economy stay the same, then the penetration of the CCS technologies will depend solely on the carbon price. Figure 4 shows how the carbon price varies in the different policy scenarios. One can notice that as the restrictions are less stringent and the trade in permits is allowed, the carbon price decreases. We know from the partial equilibrium analysis that the CCS technologies are less competitive the lower the carbon price is; therefore, it is understandable when CCS technologies enter the market less when the carbon price is lower and more when the carbon price is higher.

Figure 12. Graphical Model of How Total Costs Change as Prices Change



In the general equilibrium world, the costs, TC', and emissions, ?, can change as prices change in the economy. If carbon prices rise, for example, conventional electricity in the United States will respond by becoming cleaner, i.e. average emissions, ?, will become smaller in conventional electricity. This reduction in emissions can be seen in Figure 12 as a leftward movement on the x-axis by conventional electricity. As a result, the carbon price at which one is indifferent between technologies (the slope of the line connecting technologies) increases. Figure 12 can also show the general equilibrium effects of changing fuel prices. As coal prices fall and gas prices rise, the coal capture plant eventually becomes cheaper than the gas capture plant. Thus, the graphical representation provides one with a mini-model of costs and emissions change due to price changes. This can help one understand the results of the EPPA model.

4.4 Sensitivity Analysis

The results of the above section are expanded by investigating how sensitive the results are to 1) changes in the implementation of the CCS technologies and 2) changes in EPPA parameters. The results will change to the extent that the carbon price is changed or the total costs of the competing technologies change. In general, the changes in the CCS implementation changes the total costs of the CCS technologies the most, and changes in EPPA change the total costs of competing power technologies the most.

I change the basic factors of the CCS implementations---cost of the CCS technologies, elasticity of substitutions, and structure. I also change the most important factors in the EPPA model---substitutability between gas and coal and availability of backstops.

4.4.1 Changes in the CCS implementations

Changes in the CCS implementations change either the costs in the base period or how these costs can change over time. Whereas the structure and elasticity of substitutions change the way costs can change over time, the biggest factor is where the costs are in the base period. This is determined by the sum of the factor shares.

4.4.1.1 Sensitivity to Cost of the CCS technology

Changes in the total cost of the CCS technologies affect their competitiveness more than any other change in their implementation. The total cost is changed by changing the sum of factor shares for the technologies. To investigate the effects of a technological advance in the CCS technologies, I investigated the cheaper base year parameterizations of Table 7—STI and LTI. As expected, the cheaper the total costs of a technology, the more the technology will be used and the earlier it will enter the market. Table 9 describes how the CCS technologies behave when they are cheaper. The main differences are that the LTE and STI parameterizations enter sooner and in the later time periods, their market share is higher. As Table 9 suggests, the gas capture technology could enter the US electricity sector in 2015 under the no trading scenarios. However, because trading allows for cheaper reductions outside of the United States, the CCS technologies would not be economic in scenarios with trading until about the year 2025.

4.4.1.2 Sensitivity to Elasticity of Substitution Parameters

Changing the elasticity of substitutions in the CCS implementation affects the results only slightly. For each parameter, a range of values from zero to triple the original parameter was investigated. No combination of changes in the parameters altered the results in terms of output from the CCS technology, GDP, or carbon price by

Table 9. Scenario Results for Different Sum of Factor Shares

	Time of Entry	Carbon Price at Entry	Maximum Market Share Attained (Year Attained)
Kyoto No Trading			
LTI	Gas-2015 Coal-2025	\$40/ton CO_2 \$50/ton CO_2	Gas-68% (2060) Coal-48% (2100)
STI	Gas-2015 Coal-2090	\$40/ton CO_2 \$80/ton CO_2	Gas-42% (2080) Coal-22% (2100)
TOD	Gas-2050 Coal-2085	\$90/ton CO_2 \$125/ton CO_2	Gas-13% (2080) Coal-23% (2100)
Stabilization No Trading			
LTI	Gas-2010 Coal-2020	\$40/ton CO_2 \$50/ton CO_2	Gas-68% (2060) Coal-48% (2100)
STI	Gas-2010 Coal-2080	\$40/ton CO_2 \$93/ton CO_2	Gas-82% (2075) Coal-22% (2100)
TOD	Gas-2035 Coal-2070	\$83/ton CO_2 \$134/ton CO_2	Gas-41% (2080) Coal-56% (2100)

more than 3%. Changes in the flexibility of factor substitution affected the time of entry and the level of penetration slightly, because alterations in substitution parameters change the cost competitiveness of a technology by making it harder to switch to cheaper inputs. Therefore, a Leontief representation (no substitutability between inputs) is slightly more expensive and a flexible representation (high elasticity of substitutions) is slightly cheaper.

4.4.1.3 Sensitivity to Structural Changes

The effects of structural changes are somewhat ambiguous. I will argue that structural changes to the CES representation do not affect the results significantly. Investigating structural changes is not exactly straightforward; one can combine the capital, labor, fuel, fixed factor, and intermediate inputs in many different ways. Only a couple of the combinations make economic sense and of the ones that do make some economic sense, it is difficult to discern if they differ in terms of true structural differences or only by elasticity of substitutions. By reviewing previous work done at MIT and conducting my own analysis of different representations, I conclude that if one evaluates different structural representations of CCS in the current EPPA framework that have the same total cost and similar substitution parameters, then the results will not differ significantly.

In previous work with CCS technologies in the EPPA framework done, Leung (1997) investigates three different structural representations of a coal-based CCS technology—a Leontief, a two-layer structure where captured CO_2 is an intermediate good, and a CES representation. Her results show differing levels of market penetration for each structure across regions, but the conclusions do not elucidate the reasons for the different results. She points out that her results are counterintuitive because the Leontief structure is cheaper than the CES, and suggests that this is because it is not clear if the Leontief and the CES are actually of equal cost in the base period. Determining whether or not they are of equal cost is difficult because she does not clarify exactly how the different representations compete on total costs, how the total costs differ across regions and how total costs are affected by the different representations. She does explain that the Leontief structure is more rigid and cannot substitute cheaper inputs as easily, but she does not clearly explain why the Leontief representation ends up being more competitive or why the CCS technology enters more in some regions.

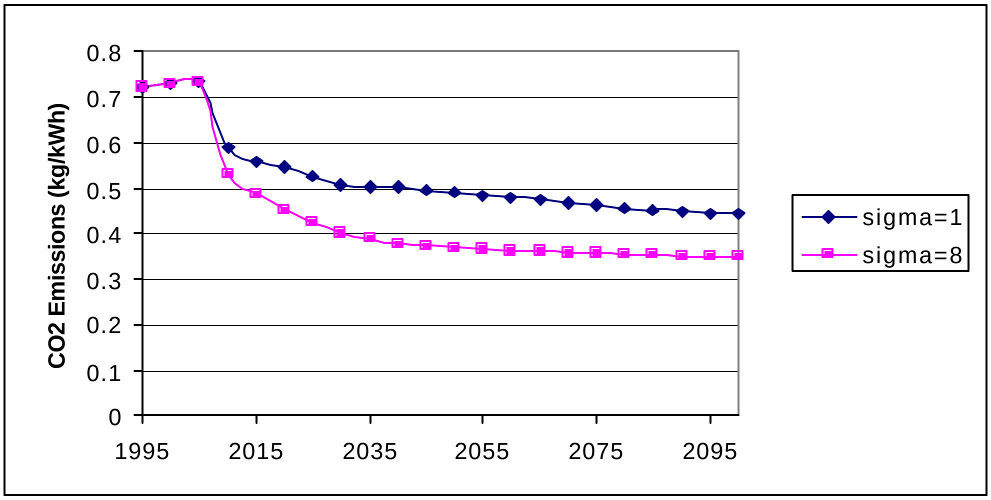
I evaluated two different representations that in my view both made economic sense. I kept the total costs of the two representations equal and evaluated them under several different policy scenarios including Stabilization and Kyoto. The results for CCS output, GDP, and carbon price in discrete time periods never varied more than 1% from each other. To ensure that I was testing the structural integrity rigorously, I evaluated more representations, but it was my judgment that over time the relative inputs of capital, labor and fuel did not correspond to what the engineering science told me was possible.

4.4.2 Changes in EPPA

4.4.2.1 Sensitivity to an Increased Ability to Substitute Gas for Oil and Coal

I test the effect of an increased ability of the conventional electricity sector to substitute gas for oil and coal as an input for power generation. The base scenario has a value of 1.0 for the elasticity of substitution. I also consider values of 2.0 and 0.5, but their differences were so small that they cannot be discerned in a graph. The following graph shows the differences in the emissions paths when comparing a value of 8 versus 1 for the elasticity of substitution between gas and the oil/coal bundle.

Figure 13. Emissions from Conventional Electricity in USA with Different Fuel Substitution Parameters



The increased flexibility to switch to gas decreases total cost of conventional electricity by decreasing the emissions costs. Therefore, the carbon price decreases and the relative cost of the CCS technologies increases. This change can also be seen in Figure 12 by noticing the effects of what happens to the relationship between conventional electricity and the CCS technologies as conventional electricity decreases emissions. With the higher fuel substitutability, the CCS technologies enter much later or not at all. This result can be misleading because it does not necessarily mean that if real world production switches to gas more easily, the CCS plants will become less competitive. Instead, the result suggests that a different representation of the CCS technologies could be needed in EPPA to make sure the relative economics of the CCS technologies is correct.

4.4.2.2 Sensitivity to the Availability of Other Backstops

I investigated how the availability of a carbon-free backstop could affect the results and realized that such an exercise did not help the analysis. Investigating the carbon-free backstop involves the same process as investigating the CCS technologies and is thus laden with the same problems. One must determine when the backstop is available, how much it will cost, how fast it can penetrate, etc. Indeed, numerous technologies could be implemented into EPPA, but I do not believe that this would be instructive at this time. Instead, I believe that the partial equilibrium framework that I introduced provides a suitable framework for one to understand how competitive a CCS technology will be against alternative sources for power. Furthermore, one could argue that changing the elasticity of substitution between the value added and fuel bundles in the conventional electricity sector would allow the model to incorporate an increased ability to produce electricity from less fuel intensive sources.

4.5 Drawbacks of Modeling in EPPA

Because the EPPA model sacrifices some technical detail for the ability to focus on broader market interactions, one has difficulty 1) deciphering exactly which technologies are being used in conventional electricity production, 2) one has a hard time introducing new discrete technologies, and 3) and one cannot look at the economics on the project level. As discussed earlier, no one single model can do everything. Luckily, there are other approaches that can build upon the approach used in this thesis.

4.6 Comparison to other Modeling Efforts of CCS technologies

The EPPA model is but one example of how to model energy-economic interactions and the economics of CCS technologies in particular. The different approaches that are available are often broadly categorized into two main approaches—top-down and bottom-up. Bottom-up models are those that focus on analyzing many different discrete technologies whereas top-down models are those that focus more on market interactions and generally do not provide much technical detail. The EPPA model is an example of a top-down approach that does not represent specific power generation technologies. Furthermore, the EPPA model can be differentiated by its general equilibrium nature. Other models represent up to a thousand different discrete technologies and cannot take general equilibrium effects into account.

4.6.1 Top-Down vs. Bottom-Up[11]

The top-down approach encompasses a variety of methods focusing on market interactions, trade effects, and other macroeconomic concepts. This method, commonly used by economists, does not focus on the technical detail, as would the bottom-up approach commonly used by engineers. The top-down approach focuses on prices and when analyzing a particular technology asks "At what relative prices will this technology be competitive with other technologies available?" The prices are solved endogenously and change as demand and supply change. For example, as more and more gas plants are built, the price of gas increases along with the increased demand for gas plants and gas itself. This could lead to a decrease in demand for coal and coal plants and thus result in a drop in coal prices. These changes in prices are commonly referred to as general equilibrium effects and can change the relative competitiveness of the two plants. In analyses concerning big changes to the economy like global climate change or

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[11] This discussion of top-down vs. bottom-up policy analyses closely follows the discussion presented in Jacoby, (1999).

widespread use of a new technology, these general equilibrium effects can be large. However, to represent such broad market interactions, modelers must sacrifice some detail to be able to focus on the larger interactions. For example, in the EPPA model conventional electricity is an aggregate of many different technologies. The focus is on the ability to switch among inputs, not the ability to switch between discrete technologies.

Bottom-up analyses focus on technical detail and ask "At what cost?" These analyses present technical detail and elicit the microeconomic justifications for technical choice. Problems arise when general equilibrium effects change the assumed capital, labor, and fuel input prices. Without careful attention to and understanding of market structure and inter-market interactions both the inputs into and the results out of these models can be erroneous.

4.6.2 Previous CCS modeling efforts

4.6.2.1 Pacific Northwest National Laboratory

The Pacific Northwest National Laboratory (PNNL) effort has utilized their MiniCAM model, a partial equilibrium model of the world that is focused on agriculture and energy sectors (Kim and Edmonds, 2000). Currently they are working on implementing carbon capture and sequestration technologies into a new general equilibrium model, SGM. In the MiniCAM model, the energy component has its origins in the Edmonds and Reilly Model (ERM). In the ERM model, technologies are specified by logit functions[12]. The net cost of carbon capture and sequestration is assumed to fall from \$50/t C (\$13.6/t CO_2) in 2015 to \$10/t C (\$2.7/t CO_2) by 2035. This is equivalent to a 5% penalty on the capital cost and efficiency of coal power plants and 3% penalty on the capital cost and efficiency of natural gas power plants. This is a much more optimistic assumption about technical change than used here. This thesis assumes that technical change could make the gas capture technology competitive at a carbon price of about \$48/t CO_2 (\$177/t C) instead of a carbon price of \$74.5/t CO_2 (\$273/t C).

The CCS technologies are analyzed under different policy scenarios that stabilize the concentration of carbon in the atmosphere at levels of 750, 650, 550, and 450 ppmv. In the 550 ppmv climate constraint scenario (Stabilization in this thesis assumes a 650 ppmv climate constraint scenario) the CCS technologies from predominantly coal and gas capture plants realize market shares well over 50% by 2050. The capture technologies generally enter the market between 2020 and 2035. With the use of the CCS technologies the costs of achieving the climate concentration levels is greatly reduced. The difference in the costs to the global economy, discounted by 5%, is on the order of $100 billion to $1 trillion depending on the concentration level achieved.

Even though the PNNL study has different inputs for the costs of the CCS technologies and uses a partial equilibrium model, the results do not differ much in terms of when the CCS technologies penetrate and how much market share they gain. The main difference is that this thesis shows the gas capture technologies losing market share in the later time periods, 2075 to 2100, due to an increase in the gas price.

4.6.2.2 Carnegie Mellon University

The Carnegie Mellon effort uses a bottom-up energy-economic model to analyze CCS technologies in the US electricity sector in the time frame up to 2030 (Johnson, 2000). The work in progress is focusing on the influence of the existing infrastructure, sunk costs, coal and gas prices, and the timing or carbon policies on the economic feasibility of CCS technologies. This analysis also looks to address the economic feasibility of retrofits. The preliminary results are similar to that of this thesis: in short term, up to the year 2020, NGCC plants, efficiency measures, and energy savings measures are likely to be more economical than building a carbon capture plant. In time periods after approximately 2020, CCS technologies could become economical, depending on the level of the carbon constraint as well as other factors. Since this method is focusing more on the microeconomic details in the short term, hopefully the analysis can describe what factors are most important for the market entry of CCS technologies in the short term.

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[12] For a detailed analysis see the model documentation (CIESIN, 1995).

4.6.2.3 MIT

In 1996 the MIT Joint Program on the Science and Policy of Global Change published their results of modeling CCS technologies (Eckaus *et al*, 1996). The methodology is documented in Leung (1997). The analysis used a different version of the MIT EPPA model and the approach to modeling the CCS technologies was slightly different. CCS technologies were modeled in the Annex B countries and analyzed under and AOSIS-like protocol (CO_2 reduction by OECD nations to 20% below 1990 levels by 2010). The results conclude that the CCS technologies could be competitive in scenarios without trade in permits and without significant advances in other backstop technologies. The CCS technologies enter at varying rates and attain different market shares in the Annex B regions. In scenarios with trade or significant technical advances by other technologies, the CCS technologies face considerable challenges.

4.6.2.4 Others

There are also others who would not choose to model CCS technologies. Their models, whether mental models or formal computer models, reflect their belief that emissions reductions can be attained without CCS technologies or that CCS technologies would be unacceptable. In their judgment, efficiency improvements, conservation and renewables will be able to shoulder the burden of the emission reductions without the carbon prices increasing to a point where CCS technologies are competitive.

5 Conclusions and Policy Recommendations

Modeling the CCS technologies within EPPA helped elicit and structure knowledge about the general economics of carbon capture and sequestration technologies. The modeling effort brought together results from the top-down and bottom-up perspective to improve the understanding of the competitiveness of CCS technologies and the major sensitivities thereof. The economic description in Chapter 2 presents a partial equilibrium framework to analyze the microeconomics of the capture technologies. This framework can be used to understand the model results and it can also be used to analyze the economic viability of individual cases in the short-term. The description of the modeling process in Chapter 3 describes how the capture technologies are represented within the EPPA model and touches on some of the strengths and weaknesses of this modeling approach. Chapter 4 presents the results of the modeling exercise under several policy scenarios and shows that the CCS technologies could, with carbon constraints, be economical in the United States in the future. Chapter 4 also identifies some of the key sensitivities for the model results.

The modeling results elucidate some broad economic implications for the CCS technologies in the United States. The results show that

- Efficiency improvements, energy conservation, fuel switching, and utilization of permit trading schemes are reduction measures that are economical in the short term
- To the extent that permit trading schemes are not utilized and other technologies are not developed, CCS technologies can play an important role in electricity production and meeting carbon constraints
- NGCC plants without a capture technology are likely to be built before capture plants in the immediate future—before 2020
- Gas capture plants could become economical as early as 2035 with today's technology
- Gas capture plants could become economical as early as 2015 with technological advances
- In addition to the level of technological change, the timing of when CCS

technologies become competitive depends highly on the stringency of the carbon constraints placed on the economy

- Other benefits are seen by increased welfare, a reduced carbon price, and an expansion of output in other sectors of the economy
- Output from the gas and coal industries is greatly expanded with demand for these inputs from the CCS technologies.
- Up to 38 GtC of sequestration capacity needs to be available

The general equilibrium framework also has its drawbacks. In the short-term the EPPA model's lack of sectoral and technical detail hinder its ability to analyze specific CCS projects or even CCS technologies on a regional basis in the United States. In the long-term the structural and parameter uncertainty leads to much greater uncertainty on the expected carbon price and uncertainty on the existence and costs of other power technologies. In the shorter term the partial equilibrium framework can be very useful in understanding the microeconomics of specific CCS projects. In addition the economic dispatch models used in the electricity industry could be helpful to understand the short-term prospects. In the longer term the uncertainty is greater not necessarily because the analysis method is faulty, but because nobody can predict the future. The results do show that in numerous long-term scenarios, the CCS technologies were economical. If one understands the magnitude of reductions that are needed to stabilize greenhouse gas emissions, one can easily recognize the need to have a large portfolio of technologies, possibly including CCS, which will help in reducing greenhouse gas emissions.

The discussions in this thesis will hopefully allow policy makers in government, industry and academia think more clearly about the economics of these particular CCS technologies and by doing so also help them understand the results from other economic analyses. The troubles encountered in determining the parameterization of the CCS technologies are encountered in all types of economic modeling of technologies. One should always be asking whether or not the technologies are competing on prices, how and if prices are assumed to change, what factors determine the market penetration of the technologies, and how the technology interacts with rest of the economy.

5.1 Next steps

More issues need to be addressed before a CCS power plant will be built. This thesis focuses on the broad economic picture. A more detailed analysis will need to focus on whether investing in a capital intensive CCS plant will create the risk and return that is suitable for an investor. This thesis can help structure such an analysis with the partial equilibrium framework and the results from the EPPA model. The two frameworks help an investor understand when the investment is profitable and what the risks are over the long term. However, this thesis does not fully address some of the technical and political issues that still need to be resolved and will affect the risk and return of a CCS investment.

For example, the sequestration options need to be investigated to make certain that the sinks are secure, environmentally safe, close enough to the carbon source, and publicly acceptable. Such research is currently being undertaken, but the interesting question is how much evidence of no harm will the public or government need before a power producer is allowed to sequester carbon dioxide? This tricky public relations/social policy question is difficult to answer and an investor will need to take into account the risk of sinking money into a CCS project without it enjoying public support. One could learn from the experience of other technologies like nuclear power and genetically modified organisms where public perception has been a very important factor in the actual feasibility of technology. Different levels of public opinion have given both technologies different fates around the world and could likely be an important driver for them in the future as well.

However, even if the technologies are deemed safe, the opinion could be that carbon capture and sequestration technologies are not addressing the real issue. Some do not view the issue to be purely one of reducing greenhouse gas emissions, but also one of reducing fossil energy use. This could also lead to reduced public or government support.

Several forms of regulatory risk should also be considered. I have shown that the economic feasibility depends on a strong carbon constraint being put in place. One should understand that this thesis, like many other economic analyses, assumes an efficient carbon cap-and-trade system. There are many other less efficient policies that should be considered possible including a different distribution of emissions constraints across sectors, taxes on the energy content (not the carbon content), technology forcing, or a myriad of others. In some instances the effects would be advantageous for CCS technologies and in others detrimental. For a more in depth view on this topic, Babiker *et al.* (2000) illustrates how such policies can impact the economy and Keohane *et al.* (1998) discusses why different types of environmental regulatory policies are chosen in the United States. In addition, one should also consider the role of including other gases in the regulatory framework. Reilly *et al* (1999) shows that by including other greenhouse gases the costs of meeting climate goals could be reduced, thus making CCS technologies less competitive.

5.2 Model Improvements

The problems encountered in implementing the CCS technologies suggest that some improvements could be made to EPPA's electricity sector and to the model in general. As discussed in Chapter 3, the conventional electricity is a constant marginal cost technology that aggregates all forms of electricity production other than nuclear. Fuel substitutes low in the tree to form a fuel bundle which substitutes for the capital and labor aggregate (see Figure 2). With this type of model specification, it is difficult to introduce a new technology like CCS, because it must compete against the average cost of the aggregate, not the marginal cost of one particular technology. Another problem arises because the input parameters are based on a 1995 SAM and a new, cheaper gas plant has since been introduced. This new gas technology has different costs than those in the conventional electricity sector. If one believes that this is the technology that a newly introduced technology in EPPA should compete against, then adjustments will need to be made to make the relative economics of the new technology accurate. One possible solution to this problem is to introduce a technology that represents the new gas technology. One would follow the same process that I did in introducing the CCS technologies and would also encounter the same problems with determining the fixed factor.

A couple other possible solutions could also mitigate the problems associated with fixing the bang-bang behavior of competing technologies. Firstly, one could introduce a constraint on capital expansion by a particular technology. This could more accurately represent the shortage of engineering firms. Another possible solution would be to differentiate vintaging across sectors in EPPA. Currently, a vintaging parameter determines how much of the capital stock is malleable in the next time period. This term can be thought of as representing capital depreciation in a sector and in EPPA it is constant across sectors. However, if one believes that capital in the electric sector depreciates differently than other sectors than one should consider differentiating between sectors. By having more rigid vintaging in the electric sector, the plants would effectively depreciate slower and new technologies would have a more difficult time entering.

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Appendices

Appendix A: Model Code

The implementation of the CCS technologies within EPPA involves placing the production functions in the EPPACORE.GMS file, specifying these parameters in the EPPABACK.GMS file, and then making smaller parameter adjustments in other files. The following shows the additions main additions made to the files, not the entire files.

A.1 EPPACORE.GMS

```
$PROD:EB("IGCC",R)$ACTIVE("IGCC",R) s:0 a:0.4 va(a):1.0 b(a):0 c(b):0 d(c):0.2

   O:PD(G,R)$(NOT X(G))    Q:BSTECH("IGCC","OUTPUT",G)
   I:PBF("IGCC",R)           Q:BSTECH("IGCC","INPUT","FFA")
   I:PL(R)                   Q:(BSTECH("IGCC","INPUT","L")*BADJST("IGCC",R))  va:
   I:PK(R)                   Q:(BSTECH("IGCC","INPUT","K")*BADJST("IGCC",R))  va:
   I:PA_C("COAL",R)         Q:(0.1*BSTECH("IGCC","INPUT","COAL")*BADJST("IGCC",R))  b:
   I:PK(R)                   Q:BSTECH("IGCC","INPUT","KSEQ")                          d:
   I:PL(R)                   Q:BSTECH("IGCC","INPUT","LSEQ")                          d:
   I:PA("COAL",R)            Q:(0.9*BSTECH("IGCC","INPUT","COAL")*BADJST("IGCC",R))  c:
   I:PK(R)                   Q:(.26)
   I:PL(R)                   Q:(.04)

$PROD:EB("GAZ",R)$ACTIVE("GAZ",R) s:0 a:0.4 va(a):1.0 b(a):0 c(b):0 d(c):0.2

   O:PD(G,R)$(NOT X(G))   Q:BSTECH("GAZ","OUTPUT",G)
   I:PBF("GAZ",R)           Q:BSTECH("GAZ","INPUT","FFA")
   I:PL(R)                   Q:(BSTECH("GAZ","INPUT","L")*BADJST("GAZ",R))   va:
   I:PK(R)                   Q:(BSTECH("GAZ","INPUT","K")*BADJST("GAZ",R))   va:
   I:PA_C("GAS",R)          Q:(0.1*BSTECH("GAZ","INPUT","GAS")*BADJST("GAZ",R))     b:
   I:PA("GAS",R)            Q:(0.9*BSTECH("GAZ","INPUT","GAS")*BADJST("GAZ",R))  c:
   I:PK(R)                   Q:BSTECH("GAZ","INPUT","KSEQ")                        d:
   I:PL(R)                   Q:BSTECH("GAZ","INPUT","LSEQ")                        d:
   I:PK(R)                   Q:(.26)
   I:PL(R)                   Q:(.04)
```

A.2 EPPABACK.GMS

```
TABLE  BSTECH(BT,*,*)    Backstop  technologies  (a  simple  input-output
table)


                OUTPUT.REFOIL      OUTPUT.GAS      OUTPUT.ELEC
SOLAR                                              1
SYNF-OIL            1
H2                  1              0
IGCC                                               1
GAZ                                                1

+               INPUT.K         INPUT.L       INPUT.AGRIC    INPUT.LSEQ

SOLAR            0.50            0.20            0
SYNF-OIL         0.40            0.30
H2               0.4             0.1             0
IGCC             0.85            .18                               0.01
GAZ              0.57            .13                               0.01

+                        INPUT.COAL          INPUT.REFOIL      INPUT.FFA
INPUT.KSEQ

SOLAR                                            0.01
SYNF-OIL                         0.3             0.01
H2               0.                              0.01
IGCC             0.26                            0.01              0.11
GAZ                                              0.01              0.05

+               INPUT.ELEC      INPUT.ENER     INPUT.OTHERIND INPUT.GAS

SOLAR                            0.              0.3
SYNF-OIL                         0.              0.
H2               0.6
IGCC
GAZ                                                             0.46


;
```

Appendix B: Calculations

B1: Sequestration Costs

The sequestration costs for the coal and gas plants are $3.6\frac{mills}{KWh}$ and $8.1\frac{mills}{KWh}$.

This calculation is based on our knowledge that the gas and coal plants emit $0.04\frac{kg\,CO_2}{KWh}$ and $0.09\frac{kg\,CO_2}{KWh}$, respectively, and they capture the CO_2 with 90% efficiency. Hence, the amount sequestered is calculated as such:

$0.04\frac{kg\,CO_2}{KWh}\times\frac{1}{1-0.90}=0.36\frac{kg\,CO_2}{KWh}$ sequestered for gas, and

$0.09\frac{kg\,CO_2}{KWh}\times\frac{1}{1-0.90}=0.81\frac{kg\,CO_2}{KWh}$ sequestered for coal.

The sequestration costs are thus,

$0.36\frac{kg\,CO_2}{KWh}\times 10\frac{\$}{tonne\,CO_2}\times\frac{1000\,mills}{\$}\times\frac{tonne}{1000\,kg}=3.6\frac{mills}{KWh}$ for gas, and

$0.81\frac{kg\,CO_2}{KWh}\times 10\frac{\$}{tonne\,CO_2}\times\frac{1000\,mills}{\$}\times\frac{tonne}{1000\,kg}=8.1\frac{mills}{KWh}$ for coal.

B2: Cost and Emissions Calculations for Conventional Electricity

Using the total amount of GWh produced in the United Staes from the Energy Information Agency (EIA) and total amount paid for electricity by consumers from GTAP, one calculates the average price paid for electricity:

$$\frac{23.52\times e10\ Dollars}{3558397\ GWh}\times\frac{1000 mills}{Dollar}\times\frac{1\,GWh}{1{,}000{,}000\ KWh}=66.1\ mills/KWh.$$

By using the CO_2 emissions from the electricity sector from GTAP divided by the non-nuclear electricity production from the EIA one calculates the average CO_2 emissions from conventional electricity in EPPA.

$$\frac{558.8\ million\ tons\ Carbon}{2845591\,GWh}\times\frac{42\ tons\ CO_2}{12\ tons\ C}\times\frac{1\,GWh}{1{,}000{,}000\ KWh}\times\frac{1000\,kg}{1\,ton}=0.72\frac{kg\ CO_2}{KWh}$$