ECONOMIC MODELING OF CO_2 CAPTURE AND SEQUESTRATION

Sean Biggs, Howard Herzog, John Reilly, Henry Jacoby
Massachusetts Institute of Technology (MIT), Cambridge, MA, USA

ABSTRACT
As policy makers look for strategies to reduce greenhouse gas emissions, they need to understand what options are available and under what conditions these technologies could be economically competitive. This paper explores the economics of carbon capture and sequestration technologies using the MIT Emissions Prediction and Policy Analysis (EPPA) model. We model two of the most promising carbon capture and sequestration technologies, one based on a natural gas combined cycle (NGCC) capture plant and one based on an integrated coal gasification combined cycle (IGCC) capture plant. The technologies have been fully specified within the EPPA model by production functions and we simulate how they perform under different policy scenarios. The results show how changing input prices and general equilibrium effects can influence technology choice between the coal and gas capture plants and other technologies for electricity production.

BACKGROUND AND MOTIVATION
The heightened concern about global change has aroused interest in carbon capture and sequestration technologies as a means of decreasing CO_2 concentrations in the atmosphere. Projects are already underway to research and implement such technologies in countries like the United States, Japan, Norway, and Great Britain. In the United States, the Department of Energy (DOE) is investigating the economic, technological, and social issues of carbon capture and sequestration technologies. In 1997, the President's Committee of Advisors on Science and Technology (PCAST) recommended increasing the DOE's R&D for carbon sequestration. Past research has focused on identifying research needs (for example Herzog *et al*., 1993) and assessing technical feasibility and engineering cost data (for example David and Herzog, 2000). More recently, economic modelers have sought to integrate knowledge about the economics of carbon capture and sequestration technologies into economic models (for example Eckaus *et al.*; 1996, Kim and Edmonds, 2000; and Dooley, *et al.*, 1999).

This paper summarizes our analysis of two carbon capture and sequestration technologies for power generation, 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 here refers only to these fossil power technologies and the subsequent sequestration of the captured carbon dioxide. David and Herzog (2000) identified these technologies as two of the most economically promising power plant options available. A myriad of other sources and capture processes are often considered under the umbrella of carbon capture and sequestration technologies, but these options are not evaluated here. This paper gives a brief overview of the method of analysis and the results obtained. Biggs (2000) describes the research effort in detail.

METHOD OF ANALYSIS
The MIT EPPA Model
This analysis 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 that has been developed for analysis of climate change policy. The

current version of the model is built on a comprehensive energy-economy data set (GTAP-E[1]) 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, which are linked by international trade; 9 production sectors; and 1 representative consumer for each region (see Table 1). This analysis focuses mainly on the USA region and the electricity sector.

Table 1:EPPA Regions and Sectors

Regions	Annex B (United States, Japan, European Community, Other OECD, Eastern European Associates, Former Soviet Union) and Non-Annex B (Brazil, China, India, Energy Exporting Countries, Dynamic Asian Economies, and Rest of World).
Sectors	Agriculture, Energy Intensive Industries, Other Industries, Coal, Oil, Refined Oil, Gas, Electricity, and Investment

Constant elasticity of substitution (CES) functions are used to describe 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. In the EPPA electricity sector, all non-nuclear electricity production technologies are represented by a conventional electricity production function. Specific technologies like coal power or hydroelectric are not explicitly represented. Instead, these technologies are represented by conventional electricity's ability to switch among inputs of capital, labor and fuels. Nuclear electricity production is explicitly represented as a separate electricity production technology.

Implementation of the CCS Technologies

Two discrete production functions are specified for the gas and coal capture power generation technologies. The electricity produced by each power technology (conventional, nuclear, and CCS) is assumed to be a homogenous good. The costs of the CCS technologies are specified by the sum of the factor shares in the base period, 1995. Technological advances are considered by changing the base year costs. The costs as implemented into the model are based on the engineering cost analysis performed by David and Herzog (2000) for two cases: costs for today's technology (TOD) and small technical advances (STI) possible by 2012. Equation 1 describes the total costs (TC) in mills/kWh of power generation technologies, as implemented in the base year of the model.

$$TC = TC^{*} + k \times P_{CO2} \quad (1)$$

It is made up of the total costs net of emissions (TC*) and any emissions cost. TC* is the sum of 1) the busbar costs of producing electricity, 2) the cost for transmission and distribution (assumed to be 20 mills/kWh), and 3) for capture and sequestration plants, the costs of sequestering (i.e., transport and injection) the captured carbon dioxide (assumed to be \$10/t CO_2). The emission costs are calculated by multiplying the carbon price (P_{CO2}) in \$/t CO_2 times the emissions of the power plant (κ) in kg CO_2/kWh. Table 2 describes these parameters for the capture technologies and a reference NGCC gas plant without capture technology. In addition, the carbon price at which the

[1] 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).

capture technology and the reference NGCC technology would have the same total cost is also presented.

Table 2. Costs of the CCS technologies

	TOD TC* (mills/kWh)	STI TC* (mills/kWh)	k (kg CO_2/kWh)	Equalizing P_{CO2} ($/t CO_2)	
Reference NGCC	52.0	51.0	0.37	**TOD**	**STI**
Gas Capture	76.6	69.6	0.04	75	56
Coal Capture	87.1	77.1	0.09	125	93

Capabilities and Limitations

The cost comparisons in Table 2, while valid for considering a single plant for a specific set of reference prices, are not valid for considering the economy-wide potential for CCS technologies because prices change for fuels, electricity, capital and labor when a carbon constraint is implemented. Using the EPPA model allows us to investigate how the competitiveness of the capture technologies change as prices in the economy change as well as how the use of capture technologies will change prices, production activity, and general welfare in the economy. Therefore, we introduced a representative gas and coal capture plant in EPPA, including the costs of capture and sequestration. Because of the high level of aggregation, the representation of the electricity sector and the carbon sequestration technologies in the EPPA model has some limitations, which we plan to address in future research (Biggs, 2000).

SCENARIOS AND RESULTS

The CCS technologies are analyzed under two policy scenarios, Kyoto and Stabilization (see Table 3). 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.

Table 3: 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. Non-Annex B countries have no emission constraints.
Stabilization[2]	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	Carbon permits are tradable among Annex B regions
No Trading	Carbon permits cannot be traded among regions
With CCS	CCS technologies available
No CCS	CCS technologies not available

Two variations of each scenario are analyzed, one with an international tradable permit system that allows trade among Annex B regions and one without trade among Annex B regions. Under these scenarios the CCS technologies can become economically competitive in the United States. This is

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

understandable given that the partial equilibrium analysis (see Table 2) judges today's gas capture technology to be competitive at carbon prices of \$75/t CO_2 and Fig. 1 shows that carbon prices in the United States will increase over time and break the \$75/t CO_2 barrier in time periods between 2035 and 2055.

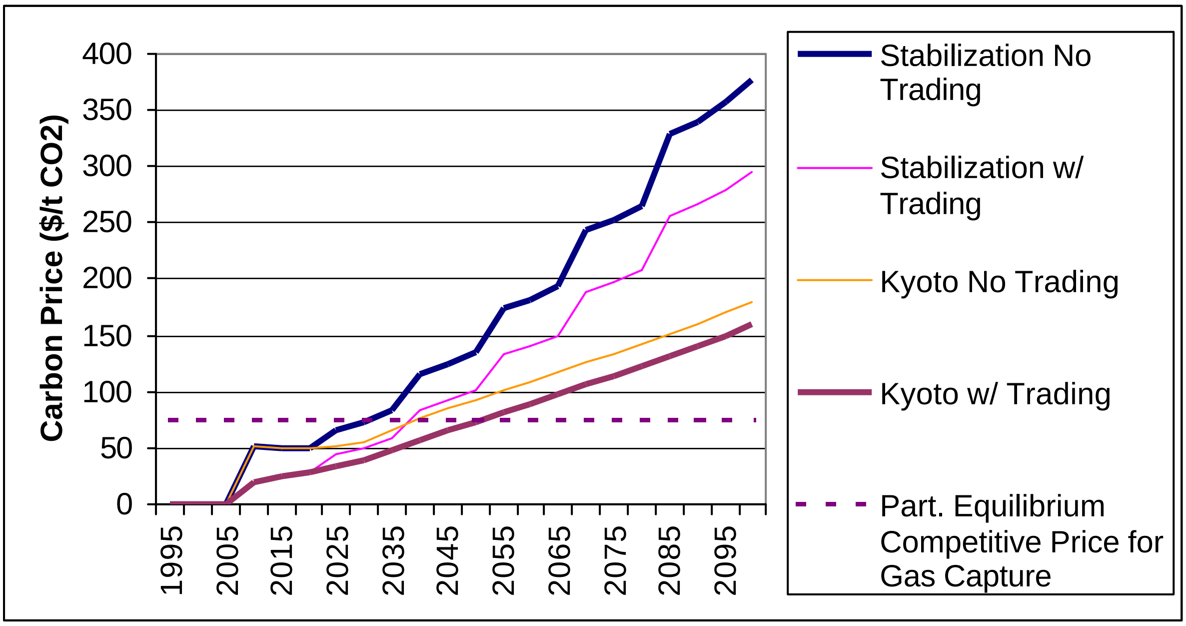

Figure 1: Carbon Prices in USA in Scenarios without CCS Availability

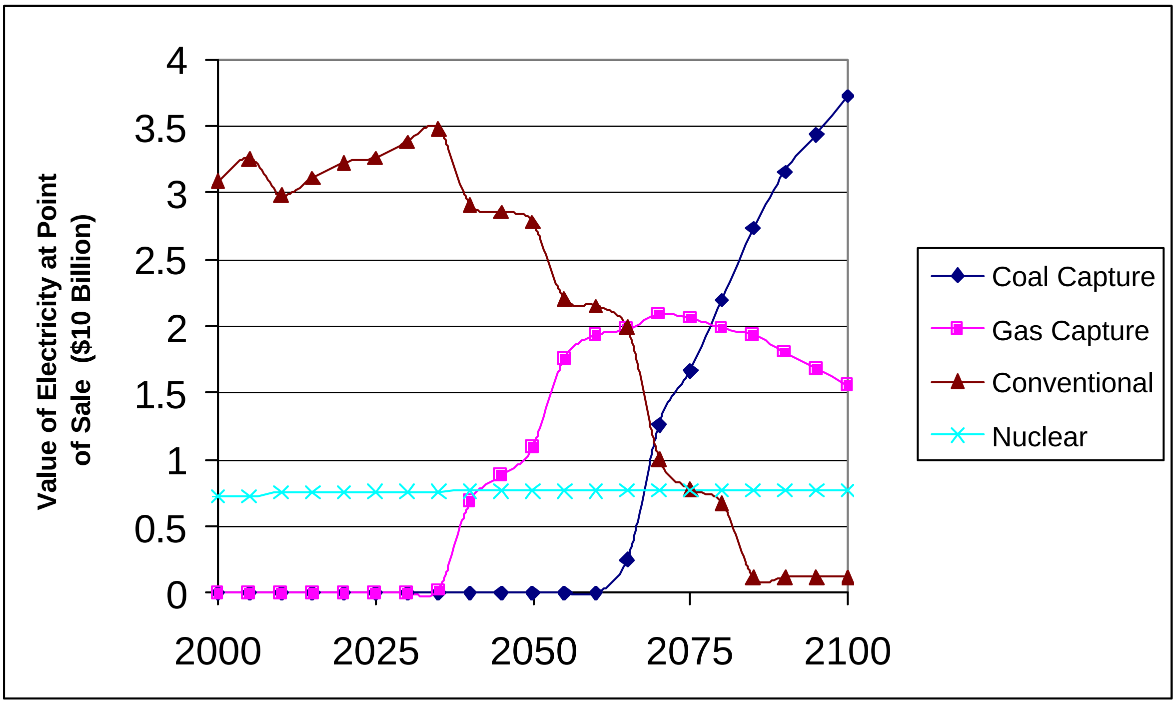

Figure 2: Value of Electricity Output from Different Sources in USA under Stabilization No Trading—Today's Technology (TOD)

The dynamics of market penetration show the gas capture technology entering first. The use of the gas capture technology increases the price of natural gas, and as the price of natural gas increases, the competitiveness of the coal capture plant improves until it enters the market. The use of the coal capture plant increases the price of coal, and the utilization of the capture technologies reduces the carbon price in the economy.

As an example, Fig. 2 illustrates the penetration of today's (TOD) gas and coal capture technologies under one policy scenario, Stabilization No Trading. In this case, 38 GtC are sequestered in the United States by 2100. Introducing CCS technologies reduces the carbon price in 2100 from about \$375/t CO_2 to \$200/t CO_2. Other effects to the economy include a slightly greater rate of GDP expansion, an increase in welfare in the United States by 1% in 2100, and expanded output from other sectors of the economy.

In other scenarios the CCS technologies enter in different time periods and attain different market shares. If permit trading is available or if the carbon constraints are smaller as in the Kyoto scenario, the CCS technologies enter later. Table 4 summarizes the timing of market entry and the maximum market shares attained for the two CCS technologies in the scenarios analyzed.

Table 4: Scenario Results for Different levels of Technical Improvements

	Today's Technology (TOD)		**Sm. Tech. Improvements (STI)**	
	Time of Entry	**Maximum Market Share Attained (Year Attained)**	**Time of Entry**	**Maximum Market Share Attained (Year Attained)**
Kyoto With Trading	Gas-2060 Coal-2085	Gas-10% (2085) Coal-46% (2100)	Gas-2035 Coal-2080	Gas-35% (2080) Coal-62% (2100)
Kyoto No Trading	Gas-2050 Coal-2085	Gas-13% (2080) Coal-23% (2100)	Gas-2015 Coal-2090	Gas-42% (2080) Coal-22% (2100)
Stabilization With Trading	Gas-2040 Coal-2060	Gas-35% (2070) Coal-62% (2100)	Gas-2025 Coal-2070	Gas-40% (2080) Coal-68% (2100)
Stabilization No Trading	Gas-2035 Coal-2070	Gas-41% (2080) Coal-56% (2100)	Gas-2015 Coal-2080	Gas-82% (2075) Coal-22% (2100)

CONCLUSIONS

We derive some broad implications for the potential of CCS technologies in the United States based on these modeling results.

- CCS technologies could play a substantial role in reducing carbon emissions but given today's costs, they would likely only be economically viable with a substantial carbon penalty.
- Widespread introduction of these technologies in the US would occur no earlier than 2035 and then only with a very stringent emission reduction policy and without international emissions trading. Under a Kyoto-forever policy without trading introduction is delayed until 2050.
- Other measures that lower cost, such as carbon permit trading, delay further the entry of carbon capture and sequestration plants.
- Benefits of using the CCS technologies 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. Their introduction causes changes in prices and this leads to a pattern where the gas CCS technology is introduced first and is later replaced by the coal CCS.

- Over the next 100 years, up to 38 GtC of sequestration capacity could be needed for sequestering carbon captured from power plants in the United States.
- There are many uncertainties in these forecasts including the potential for technological improvements in CCS technologies, the level of economic growth and reference emissions, and economic viability of other low-carbon technologies such as nuclear and solar electric power technologies.

This paper reports on a work in progress. This work has focused on developing a methodology for evaluating CCS technologies within a general equilibrium model and developing a framework for understanding the results. Future work will improve our understanding of the present results, the effects of technological change, and the economics of CCS technologies in other regions.

BIBLIOGRAPHY

Babiker M, J Reilly and I Sue Wing, "The Emissions Prediction and Policy Analysis (EPPA) Model: Update, Sensitivity, and Comparison of Results," Report, Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA (forthcoming).

Biggs S, "Sequestering Carbon from Power Plants: The Jury is Still Out," M.S. Thesis, Technology and Policy Program, MIT, Cambridge, MA (2000). Available at: <http://web.mit.edu/sequestration/SeanBiggs.pdf>

Dooley J, J Edmonds and M Wise, "The Role of Carbon Capture & Sequestration in a Long-Term Technology Strategy of Atmospheric Stabilization," Pacific Northwest National Laboratory paper PNNL-SA-30206, Washington, DC (1999).

Eckaus R, H Jacoby, D Ellerman, W Leung and Z Yang, "Economic Assessment of CO_2 Capture and Disposal," Report No. 15, Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA (December 1996).

Hertel T, *Global Trade Analysis: Modeling and Applications*, Cambridge University Press, Cambridge (1997).

David J and H Herzog, "The Cost of Carbon Capture," these proceedings (2000).

Kim S and J Edmonds, "Potential for Advanced Carbon Capture and Sequestration Technologies in a Climate Constrained World," PNNL report 13095, prepared for the U.S. Department of Energy under contract DE-AC06-76RLO 1830 (2000).

President's Committee of Advisors on Science and Technology (PCAST), "Federal Energy Research and Development for the Challenges of the Twenty-First Century," (November 1997).

Reilly J, R Prinn, J Harnisch, J Fitzmaurice, H Jacoby, D Kicklighter, J Melillo, P Stone, A Sokolov and C Wang, "Multi-gas assessment of the Kyoto Protocol," *Nature* 401: 549-55 (1999).

ACKNOWLEDGEMENTS

This work was conducted with support from the U.S. Department of Energy under award number DE-FG02-99ER62748. We gratefully acknowledge this support, as well as the encouragement of the program managers, John Houghton (BER program, Office of Science) and Bob Kane (Office of Fossil Energy). Additional support was received from the Joint Program on the Science and Policy of Global Change and the Kahn-Rasmussen Fund.