Economic Modeling of Carbon Capture and Sequestration Technologies

Jim McFarland (jrm1@mit.edu; +1-617-258-8618)
Massachusetts Institute of Technology (MIT)
Room E40-271
1 Amherst Street
Cambridge, MA 02139

Howard Herzog (hjherzog@mit.edu; +1-617-253-0688)
Massachusetts Institute of Technology (MIT)
Room E40-471
1 Amherst Street
Cambridge, MA 02139

John Reilly (jreilly@mit.edu; +1-617-253-8040)
Massachusetts Institute of Technology (MIT)
Room E40-263
1 Amherst Street
Cambridge, MA 02139

Henry Jacoby (hjacoby@mit.edu; +1-617-253-6609)
Massachusetts Institute of Technology (MIT)
Room E52-444
50 Memorial Drive
Cambridge, MA 02139

ABSTRACT

As policy makers consider strategies to reduce greenhouse gas emissions, they need to understand the available options and the conditions under which these options become economically attractive. This paper explores the economics of carbon capture and sequestration technologies as applied to electric generating plants. The MIT Emissions Prediction and Policy Analysis (EPPA) model, a general equilibrium model of the world economy, is used to model two of the most promising carbon capture and sequestration (CCS) technologies. The CCS technologies are based on a natural gas combined cycle plant and an integrated coal gasification combined cycle plant. Additionally, the role of natural gas combined cycle plants without capture and sequestration is modeled to represent a rapidly growing generation technology. These technologies have been fully specified within the EPPA model by production functions and we simulate how they perform under different policy scenarios. The results illustrate how changing input prices and general equilibrium effects influence technology choices between gas and coal capture plants and other technologies for electricity production. Results reflect the application of the technologies to the United States.

BACKGROUND AND MOTIVATION

Heightened concerns about global climate change have aroused interest in carbon capture and sequestration technologies as a means of decreasing the growth rate of atmospheric carbon dioxide concentrations. 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 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 power generation technologies as well as a generation technology without carbon capture and sequestration facilities. David and Herzog (2000) identified natural gas combined cycle generation with capture via amine scrubbing of the flue gas and integrated coal gasification combined cycle generation with pre-combustion capture of the carbon dioxide (CO_2) as two of the most promising technological options. The term *carbon capture and sequestration* (CCS) as used herein refers only to these two fossil power technologies and the subsequent capture and sequestration of the CO_2. 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. A third technology, natural gas combined cycle without sequestration, is modeled to represent new conventional generating technologies. This paper gives a brief overview of the method of analysis and the results obtained.

METHOD OF ANALYSIS

The MIT EPPA Model

This analysis utilizes the MIT Emissions Prediction and Policy Analysis (EPPA) model (Babiker *et al.*, 2001). The EPPA model is a recursive dynamic multi-regional general equilibrium model of the world economy developed for the 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 twelve regions, which are linked by international trade; nine production sectors; and a representative consumer for each region (see Table 1). This analysis focuses on the USA region and the electricity sector.

[1] This 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 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	Coal, Oil, Refined Oil, Gas, Electricity, Energy Intensive Industries,Agriculture, Investment, and Other Industries.

Constant elasticity of substitution functions are used to describe production and consumption within each region and sector. In each time interval the model solves these functions for a set of prices that clears supply and demand across regions and sectors. The functions mathematically describe how the factors of production can be combined to produce output and how consumers trade-off among goods to maximize utility. Technologies are represented by production functions that use inputs in different combinations to produce their respective goods. In the EPPA electricity sector, all fossil fuel and hydro electricity production technologies are represented by an aggregate 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. Electricity production from nuclear and solar is explicitly represented as separate production technologies.

Implementation of Carbon Capture and Sequestration Technologies

For this analysis, separate production functions were added to the EPPA model for 1) gas power generation with capture 2) coal power generation with capture, and 3) gas power generation without capture. The additional gas power generation without capture technology represents combined cycle gas generation that was not widespread at the time of preparation of the 1995 base year data. It has different cost and fuel requirements than conventional gas-fired power plants. The electricity produced by each generation technology (conventional, nuclear, solar, gas reference, gas with capture and coal with capture) 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 year, 1995. The potential for technological advance is considered by lowering the base year costs. The costs in the model are based on the engineering cost analysis performed by David and Herzog (2000) for two cases: costs for today's technology and small technical improvements possible by 2012. Equation 1 describes the delivered price (TC) in mills/kWh of power generation technologies, as implemented in the base year of the model.

$$TC = TC^* + k \times P_C \qquad (1)$$

It is made up of the total costs net of emissions, TC*, plus any emissions cost, $\kappa \times P_C$, where P_C is the price of carbon in $/t C (dollars per metric ton of carbon) and κ is the emissions constant of the generation technology in kg C/kWh. 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) the costs of sequestering (i.e., transport and storage, assumed to be $37/t C) for capture and sequestration plants. Table 2 describes these parameters for the capture technologies and the reference gas plant without capture technology. In addition, the carbon price at which the capture technology and the reference gas technology would have the same total cost in the base year is also presented.

Table 2. Costs of the CCS technologies

	TC* ***Today's Technology*** (mills/kWh)	**TC*** ***Small Technical Improvements*** (mills/kWh)	k (kg C/kWh)	**Equalizing PCO$_2$** ***with Reference Gas*** ($/t C)	
Reference Gas	52.0	51.0	0.101	**Today's Technology**	**Small Improvements**
Gas Capture	76.6	68.6	0.011	273	196
Coal Capture	87.1	79.1	0.025	460	368

Capabilities

The partial equilibrium cost comparisons in Table 2, while valid for considering a single plant for a set of reference prices, are not valid for considering the economy-wide potential for CCS technologies. When a carbon constraint is implemented, the prices of production inputs such as fuels and electricity change. The EPPA model allows us to evaluate the economic competitiveness of the CCS technologies with price changes in the general economy. Conversely, changes in prices, production activity, and general welfare due to CCS technology introduction can be investigated. The introduction of a competitive conventional technology such as gas without capture yields similar information.

Limitations

The representation of the electricity sector and the carbon sequestration technologies in the EPPA model has some limitations. First, the conventional electricity sector is represented by an aggregation of fossil fuel plants (coal, oil, and natural gas) and hydropower. Coal comprises 52% of the output in the base year. Since, EPPA does not explicitly represent each power plant, it cannot represent the cost of retrofitting particular plants. Instead, the CCS technologies are modeled as new plant constructions. In reality, the distinction between a new plant and a retrofit is blurred. Extensive modifications to plants and structures at a particular site are not uncommon in the economy and could have advantages over trying to site a completely new plant. Given the resolution within EPPA and the extent to which it affects the main results of concern, the distinction between a retrofit and a new plant primarily involves the difference in cost. The cost of CCS retrofitting compared to the cost of new plants is a subject of current study.

A second limitation within EPPA is that while the capital for technologies represented by aggregate production functions is vintaged, the capital used in modeling the CCS technologies is assumed to be perfectly malleable. Malleable capital can be allocated from CCS technologies in one period to other uses in another sector (agriculture, other industries, etc.) in the next period.

In reality, capital invested in capture power plants and sequestration would not be readily switched to other sectors. This feature has little effect on the analysis of CCS technologies so long as the capital stock in the sector is growing over time. However, it permits capital invested in a CCS technology to be diminished and reallocated if the technology is no longer competitive. This effect is apparent in a rapid decline in CCS capacity when CCS technology becomes uncompetitive. Capital malleability of CCS technologies is the subject of on-going research and model development.

SCENARIOS AND RESULTS

The adoption of CCS technologies in the United States is analyzed under policy scenarios based on the Kyoto Protocol. The model results are compared to the reference scenario and to the Kyoto scenario without CCS technologies. Several variations of the scenario are analyzed to study conditions under which CCS technologies could be competitive (see Table 3). These variations include the tradability of carbon permits and future technical improvements.

Table 3: Policy Scenario Definition and Variations

Scenario	**Description**
Reference	No carbon constraints in any regions.
Kyoto	All Annex B countries reduce to Kyoto constraints in 2010 and remain at these levels through 2100. Non-Annex B countries have no emission constraints.
Variation	
Trading	Carbon permit trading is implemented among Annex B regions.
STI	Small, cost-saving, technical improvements may be available by 2012.

Under the Kyoto no-trading scenario, carbon prices reach \$270/t C in 2010, the first year Kyoto constrains carbon emissions (see Figure 1). A partial equilibrium calculation indicates that gas capture technology becomes economically attractive at a carbon price of \$273/t C at 1995 prices. However, we assume the earliest date CCS technologies could be made available is not until 2020 at which time carbon prices are \$330/t C. As Figure 1 illustrates, by 2100 the CCS technologies reduce carbon prices by 30% under Kyoto no-trading. CCS technologies have a less dramatic effect under trading scenarios since carbon prices grow slower. In all scenarios, other effects to the economy include a slightly greater rate of GNP expansion, an increase in welfare in the United States between 0.3% and 0.5% in 2100, and expanded output from other sectors of the economy.

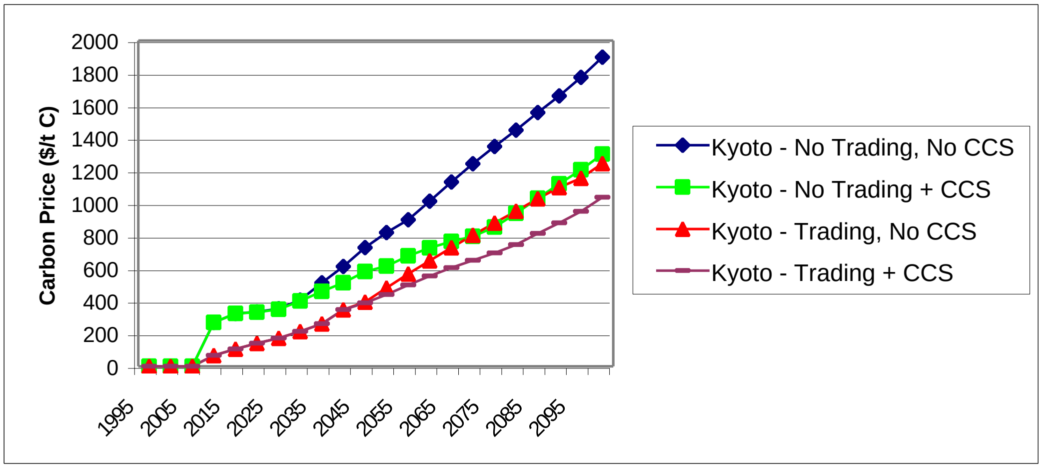

Figure 1: Carbon Prices in USA Under Kyoto Scenarios

The dynamics of market penetration show increasing share growth in natural gas combined cycle without capture from 2000 through 2015 under all scenarios including reference (see Figure 2). Gas generation offers cheaper, less carbon intensive production than the coal-dominated conventional electric sector.

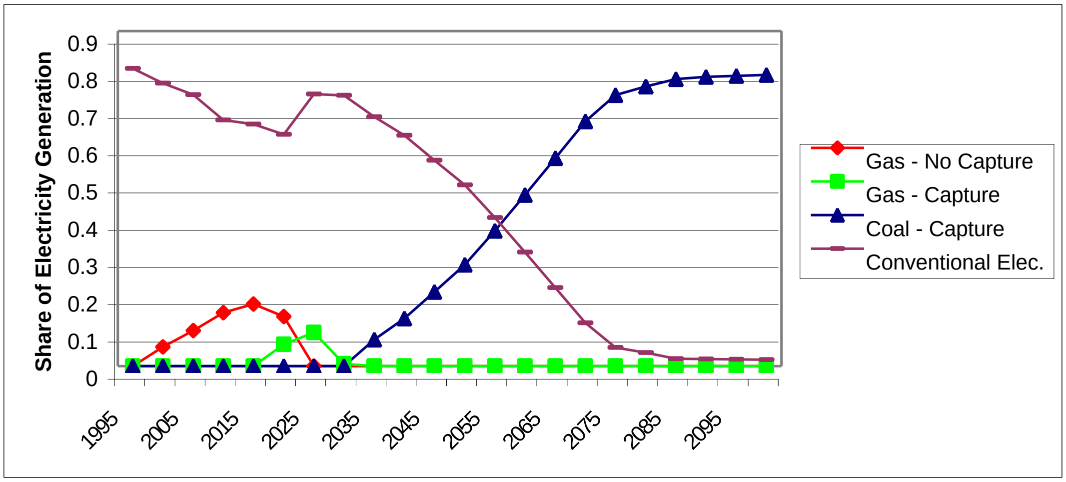

Figure 2: Share of Electricity Generation by Source in USA Under Kyoto No-Trading Today's Technology (TOD)

Under the Kyoto no-trading case, the gas capture technology enters the market in 2020, reaching a maximum share of 9% by 2025 (see Figure 2). Rising natural gas prices for gas-fired generation, both with and without capture, makes gas-fired generation exit the market by 2030. The capital malleability assumption permits a relatively rapid exit of these technologies. This decline in production of electricity from the gas generation technology requires further investigation. Under the fuel prices we project, gas generation with and without capture is economically competitive for a only short period of time. Even with modifications to capital malleability and retrofitting, escalating natural gas prices are likely to force gas with capture out of market between 2030 and 2035.

Coal capture technology enters the market in the Kyoto no-trading case in 2035 at a carbon price of $458/t C. This price is equivalent to the base year partial equilibrium price. We model entry as limited by a scarce, technology-specific fixed factor that endogenously grows as a function of actual production in the previous period. This feature represents recognized limits to rapid expansion of a new industry. Coal capture gains share at an average rate of 1.5% per year from an initial share of 7% to 75% in 2080. Share growth then slows to 0.15% per year as the technology competes with carbon-free technologies such as nuclear and solar. Nuclear and solar comprise the remaining 20% of electricity production.

In other scenarios the CCS technologies enter in different time periods and attain different market shares. In Kyoto with trading, gas with capture does not become economically viable. Lower carbon prices extend the viable life of the gas without capture technology while delaying the entry of coal capture technology until 2045. However under both scenarios, coal capture enters ten to fifteen years earlier with small technical improvements. Regardless of entry time, coal capture technology achieves roughly 80% market share due to relatively low fuel prices. Table 4 summarizes the timing of market entry and the maximum market shares attained for the CCS technologies in the trading and no-trading scenarios. The effects of implementing small technical improvements to the CCS technologies are also considered.

Table 4: Scenario Results for Different levels of Technical Improvements Through 2100

	Today's Technology				**Small Technical Improvements**			
	Gas Capture		**Coal Capture**		**Gas Capture**		**Coal Capture**	
	Time of Entry	Max Share	Time of Entry	Max Share	Time of Entry	Max Share	Time of Entry	Max Share
No-trading	2020	9%	2035	78%	2020	12%	2020	80%
Trading	-	0%	2045	80%	-	0%	2035	81%

Qualitatively these results are similar to earlier efforts to implement carbon capture technologies in EPPA. Quantitatively the results differ. Biggs, *et al*. found that gas capture was competitive from 2050 through 2100 with the Kyoto no-trading scenario. In the current analysis gas prices are higher and as a result gas capture is competitive for only a short period. This difference is indicative of the sensitivity of results to fuel prices that, as the past few years reveal, are highly uncertain.

CONCLUSIONS

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

- CCS technologies could play a substantial role in reducing carbon emissions, but would only be economically viable with policy constraints on carbon dioxide emissions.
- Gas technology without carbon capture would be a cost effective near-term solution for electricity as it has relatively low carbon emissions.
- Measures lowering carbon prices, such as carbon permit trading, delay the entry of carbon capture and sequestration technologies.
- Benefits of using the CCS technologies are seen through increased welfare, reduced carbon price, and an expansion of output in other sectors of the economy.
- The availability of CCS technologies in the policy scenarios leads to a smaller reduction in the demand for gas and coal than from the reference demands.
- The primary uncertainties in these projections include the potential for technological improvements in CCS technologies, fuel prices, the level of economic growth and reference emissions, the carbon dioxide emission constraints, and economic viability of other low-carbon technologies such as nuclear and solar electric power technologies, and the details of policy implementation such as permit trading.

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

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