ECONOMIC MODELING OF THE GLOBAL ADOPTION OF CARBON CAPTURE AND SEQUESTRATION TECHNOLOGIES

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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 computable general equilibrium model of the world economy, is used to model carbon capture and sequestration (CCS) technologies based on a natural gas combined cycle (NGCC) plant and an integrated coal gasification combined cycle (IGCC) plant. These technologies have been fully specified within the EPPA model for all regions of the world by production functions. We simulate the adoption of these technologies under scenarios with and without carbon taxes. The results illustrate how changing input prices and general equilibrium effects influence the global adoption of carbon sequestration technologies and other technologies for electricity production. Rising carbon prices lead first to the adoption of NGCC plants *without* carbon capture and sequestration followed by IGCC plants *with* capture and sequestration as natural gas prices rise.

INTRODUCTION

Heightened concerns about global climate change have stimulated 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 the United Kingdom. In the United States, the Department of Energy (DOE) is investigating the economic, technological, and social issues of carbon capture and sequestration technologies. Past research has focused on identifying research needs and assessing technical feasibility and engineering cost data [1,2].

More recently, economic modelers have sought to integrate knowledge about the economics of carbon capture and sequestration technologies into economic models [3,4,5].

This paper summarizes our analysis of two electricity generation technologies with carbon capture and sequestration as well as a generation technology without carbon capture and sequestration. David and Herzog [1] 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 for producing electricity with low CO_2 emissions. 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. Many other energy 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 (NGCC) without sequestration, is modeled to represent advanced conventional generating technologies. This paper gives a brief overview of the method of analysis and the results obtained from introducing these technologies into multiple regions of a general equilibrium, global economic model. This analysis expands upon previous work [3] by introducing CCS technologies into multiple regions.

METHOD OF ANALYSIS

The MIT EPPA Model

This analysis utilizes the MIT Emissions Prediction and Policy Analysis (EPPA) model described by Babiker, *et al* [6]. 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 [7], 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 through 2100 to capture the long-term dynamics of resource scarcity and capital stock turnover. EPPA consists of twelve regions, which are linked by international trade, nine production sectors, and a representative consumer for each region (see Table 1).

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 period the model solves these functions for a set of prices that clear supply and demand across all 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 EPPA's conventional electricity sector, all fossil fuel-based generation technologies are represented by an aggregate production function. Specific technologies such as coal-fired plants or gas-fired turbines are not explicitly represented. Instead, these technologies are represented by conventional electricity's ability to switch among inputs of capital, labor, and fuels. Technologies for electricity produced from nuclear, hydro, biomass, wind and solar are explicitly represented.

Implementation of Carbon Capture and Sequestration Technologies
For this analysis, separate production functions were added to EPPA for 1) coal power generation *with* CCS (coal capture), 2) natural gas combined cycle power generation *with* CCS (gas capture), and 3) natural gas combined cycle power generation *without* CCS. The NGCC without carbon capture and sequestration technology represents a technology that was not widespread at the time of preparation of the 1995 base year data, but is widely seen as the most likely technology to be installed where new capacity was needed. The electricity produced by each generation technology (conventional fossil fuel, nuclear, wind, etc.) is assumed to be a homogenous good and readily tradable within a region.

Specification of the production functions consists of determining the cost of electricity from the technology, the factor shares of capital, labor, and energy required for electricity production, and the ability to substitute between the various factors of production. Costs CCS technologies are based on the bottom-up engineering cost analysis performed by David and Herzog [2] which assume small technical improvements prior to commercial availability in 2015. We view the full cost of electricity as composed of the components identified in Eqn. 1, which includes the unit costs of generation, transmission and distribution (T&D), sequestration, and value of carbon emitted to the atmosphere. Equation 1 can be used to see how, from a partial equilibrium perspective, different generation technologies compare as the price of carbon changes.

$$C_{Electricity} = C_{Generation} + C_{T\&D} + C_{Sequestration} + \kappa P_{Carbon} \quad (1)$$

Transmission and distribution costs and shares were derived from U.S. data [8]. Sequestration costs are assumed to be constant at $37 per tonne carbon, while emission costs are determined by a technology-specific emissions constant, κ, and the price of carbon ($ per tonne carbon). The first column of Table 2 presents the total cost of electricity net emission costs based on these data. Comparing the electricity costs of these new technologies to the cost of conventional power in the U.S. at 66 mills per kilowatt-hour, we see that advanced gas generation without CCS is 16% less expensive. Gas and coal CCS technologies are respectively 8% and 25% more expensive. When introducing these technologies into other regions, we assume the ratio of the cost of electricity from the new technologies to conventional technologies remains constant across regions as do the shares of capital, labor, and fuel. Holding input prices fixed and using Equation 1, the carbon price at which the capture technologies and non-capture technologies have the same total cost of electricity can be determined. The last column in Table 2 presents these partial equilibrium carbon prices for a conventional pulverized coal technology and the advanced natural gas technology. Compared with the pulverized coal technology, the gas CCS technology becomes competitive above $36/tonne C at current natural gas prices. The coal CCS technology requires a higher carbon price of $90/tonne C. These prices may overstate the attractiveness of the capture technologies. Compared to the advanced natural gas technology, the gas capture technology becomes competitive at $190/tonne C, roughly half that of the $375/tonne C required for the coal capture technology.

TABLE 2
TECHNOLOGY COSTS

Technology	Cost of : Generation, T&D, Sequestration (mills/kWh)	Electricity Cost Ratio of New Tech. to Conventional Tech. @ 66 mills/kWh	Emissions Constant, κ (kg C/kWh)	Partial Equilibrium Carbon Entry Price vs. *Pulverized Coal, NGCC* Technology ($/tonne C)
Advanced Gas (NGCC)	55.3	0.84	0.092	
Gas + Capture, Seq.	71.0	1.08	0.010	$36 - $192
Coal + Capture, Seq.	82.3	1.25	0.020	$90 - $375

In addition to the three inputs to production mentioned above, each technology is modeled to require a small share (1%) of a technology-specific fixed factor. The fixed factor represents various technology-specific inputs that limit the rate of penetration of a technology, but not the ultimate level of demand. The amount of fixed-factor is initially limited but grows as output expands. In the context of large-scale electricity generating technologies, this may be thought of an initially limited amount of engineering capacity to build and install new plants or a regulatory process that slows installation. We specify a technology's fixed factor supply grow endogenously with the level of output and posit a functional form with S-shaped growth. Without a fixed factor, technologies would immediately capture very high share of electricity production, an unrealistic proposition.

Capabilities

The EPPA model allows us to evaluate the economic competitiveness of the CCS technologies as prices, output levels, and other conditions change in the general economy. 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. 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 natural gas combined cycle without capture yields similar information.

EPPA also accounts for the stock nature of capital through an explicit vintaging of capital investments within the electric power sector. Vintaged capital retains the input shares it had when installed until it has depreciated; that is there is no ability to substitute among inputs once the capital is in place. Capital investments in EPPA are tracked by vintage and depreciate over a twenty year period. For this version, we further assumed that capital could not be reallocated out of the new electric generating technologies. While normally not an issue for other EPPA sectors [9], given the rapidly changing conditions in the electric sector with carbon policies we found a tendency for the solution to unrealistically allocate vintaged capital out of the CCS technology. By fixing capital to the technology, we more accurately capture the exit and entry dynamics of technologies [3]. Without fixed capital, a technology's output drops to zero when it becomes uneconomic since capital is not stranded in an utilized asset.

Limitations

The representation of the electricity sector and the carbon sequestration technologies in the EPPA model has some limitations. First, 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 somewhat 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, and it may be largely semantics as to whether a completely rebuilt plant at an existing site is a retrofit or a new plant (although the semantics have regulatory repercussions as US environmental regulations distinguish new sources from existing power plants emissions). 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. In fact, only a fraction, ϕ, of each years investment is vintaged. The remaining stock $(1-\phi)$ remains malleable, reflecting the fact that there is an ability, albeit limited, to retrofit capital. Second, this same aggregation prohibits consideration of electricity market effects such as plant dispatch and transmission constraints. In ongoing work we are studying the implications of retrofitting on sequestration technology adoption.

SCENARIOS AND RESULTS

The adoption of CCS technologies in the United States is analyzed under a reference scenario without constraints on greenhouse gas emissions and under a scenario where a tax is placed upon carbon. Carbon taxation begins in 2010 at $50/ tonne C and increases by $25/ tonne C every five years reaching a maximum of $200/ tonne C by 2040. The model results are compared to the reference scenario and to a scenario without CCS technologies.

In the reference scenario, electricity production increases nearly five-fold over the modeling time frame from 13 trillion kilowatt-hours (TkWh) in 1995 to 64 TkWh in 2100 as shown in Figure 1. The share of advanced natural gas reaches 18% of total generation by 2020, but declines to 4% of generation by 2055. Conventional generation, primarily from coal, accounts for over 65% the electricity generation after 2035 and attains a 78% share by 2060.

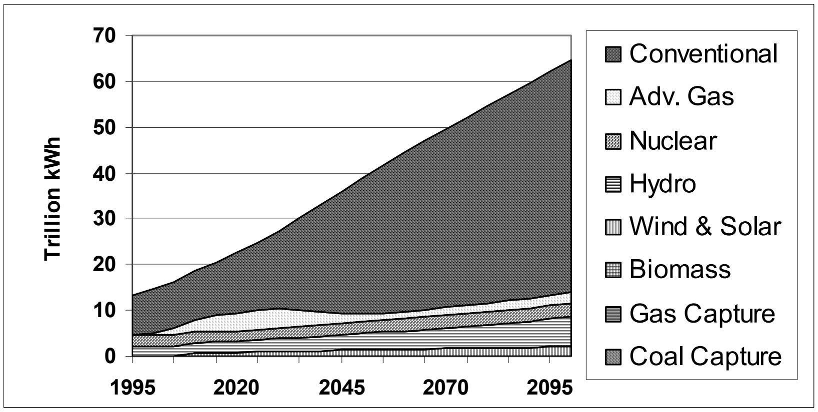

Figure 1: Global Electricity Production – Reference Scenario

Under the tax scenario, the contributions from the production technologies change substantially while the total electricity production in 2100 is reduced by 11%. The advanced gas technology without capture expands rapidly from 2005 to 2040 as Figure 2 illustrates. The gas capture technology enters the market in 2015 at a $75/ tonne C. Rising natural gas prices reduce the share of generation from these technologies after 2040. The coal capture technology enters the market in 2025 even though the carbon tax is less than half of the partial equilibrium carbon entry price, as suggested in Table 2, when compared to the advanced gas technology. Rising natural gas prices drive this behavior as they make the gas technology much more expensive than that represented in Table 2. The rise in gas prices depends on specifics of the resource model in EPPA—if there were unlimited, low cost sources of gas then prices need not rise. EPPA bases its estimates of gas resources on USGS estimates of gas and includes a technology to produce synthetic gas from coal.

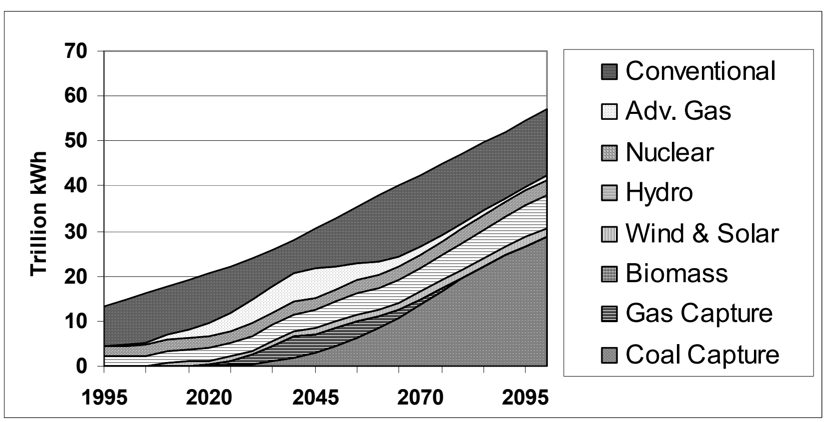

Figure 2: Global Electricity Production – Tax Scenario

The trends and timing of adopting gas technologies both with and without capture followed by advanced coal capture are exhibited across all regions except for Japan, the European Community and India. Base-year electricity prices in Japan and the European Community are at least 43% higher than the average prices of the other regions. High electricity prices inflate the effect of the electricity cost ratio parameter (see Table 2) and make the sequestration technologies economically unattractive. The advanced gas technology accounts for the majority of Japan's electricity after 2025. The European Community gradually replaces conventional coal technology with advanced gas until 2045 when the region reverts to conventional coal. In simulations with carbon prices of $300/ tonne C, the European Community switches to advanced coal capture after 2045. India, lacking substantial gas reserves, adopts the advanced coal capture technology in 2035 and bypasses investments in advanced gas technologies.

CONCLUSIONS

We derive some broad implications for the potential of CCS technologies 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, but given the representation of gas resources in the EPPA model, it is not competitive with coal with sequestration in the longer term.
- Coal technology with carbon capture offers a cost effective long-term source of low carbon emitting electricity.
- Benefits of using the CCS technologies are seen through increased electricity production and lower electricity prices.
- The availability of CCS technologies in the policy scenario 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 taxation and permit trading.

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REFERENCES

1. David, J. and Herzog, H.(2000). In: *Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies*, pp. 973-978.
2. David, J. (2000). S.M. Thesis, M.I.T., United States.
3. McFarland, J., Herzog, H., Reilly, J. and Jacoby, H.D. (2001). In: *Proceedings of the First National Conference on Carbon Sequestration*, netl.doe.gov/publications/proceedings/01/carbon_seq/2c3.pdf.
4. Eckaus R., Jacoby, H., Ellerman, D., Leung, W. and Yang Z. (1996) Report No. 15, Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA.
5. Kim, S. and Edmonds, J., (2000) Pacific Northwest National Lab report 13095.
6. Babiker, M.H., Reilly, J.M., Mayer, M., Eckaus, R.S., Sue Wing, I. and Hyman, R.C. (2001) Report No. 71, Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA.
7. Hertel T., (1997) *Global Trade Analysis: Modeling and Applications*. Cambridge University Press, Cambridge.
8. U.S. Department of Energy (1999). Supporting Analysis for the Comprehensive Electricity Competition Act.
9. Jacoby, H.D. and Sue Wing, I. (1999). *The Energy Journal* **20**, 73.