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THE ROLE OF CARBON CAPTURE & SEQUESTRATION IN A LONG-TERM TECHNOLOGY STRATEGY OF ATMOSPHERIC STABILIZATION

JJ DOOLEY, JA EDMONDS, and MA WISE
Pacific Northwest National Laboratory
901 D St, S.W. Suite 900
Washington, D.C. 20024

ABSTRACT: In this paper, we examine the potential of carbon capture and sequestration technologies to make a significant contribution to national and global efforts to control carbon dioxide (CO_2) emissions. We examine the performance of these technologies under two alternative future energy-policy scenarios. We conclude that carbon capture and sequestration technologies could indeed play a significant role in reducing atmospheric concentrations of CO_2 and could reduce the costs associated with stabilizing atmospheric concentrations of CO_2 by 35% or more.

KEY WORDS: Carbon capture and sequestration, atmospheric stabilization, economic modeling.

The scientific literature shows that the stabilization of atmospheric carbon dioxide (CO_2) concentrations requires that in the long-term, regardless of the concentration at which stabilization is to be affected, the free venting of carbon must be globally and systematically reduced (IPCC, 1996a). This result is usually taken to mean that fossil fuel use must be globally, systematically reduced. That conclusion is erroneous. Control over CO_2 emissions can not only be achieved by curtailing the use of fossil fuels, but also by applying technologies which capture and sequester (or recycle) carbon. While there is an abundant literature on the issue of atmospheric stabilization (IPCC, 1996b), this literature is deficient in that it has largely ignored the availability of technologies, which could capture and sequester carbon.[1]

MODELING FUTURE CARBON EMISSIONS

In order to carry out our analysis of the performance of carbon capture and sequestration technologies and their possible contribution to reducing carbon emissions, we employ the energy, agricultural-land-use, and carbon cycle components of the MiniCAM model, version MiniCAM 98.3. MiniCAM 98.3 is an integrated assessment model of global change with a focus on the world's energy and agriculture systems. This is an updated version of the MiniCAM model described in Edmonds et al (1998), and Edmonds et al (1996). MiniCAM 98.3 differs from previous versions of the model in that it incorporates carbon scrubbing and sequestration technology options, a hydrogen fuel option, and a global market for biomass energy. Carbon capture is explicitly represented in the model at key fuel transformation nodes, and carbon is captured and sequestered if economics are favorable or if policy mandates it.

MiniCAM 98.3's reference scenario is intended to reflect in large measure a continuation of many present trends. We assume that global population will eventually stabilize at approximately eleven billion people. We assume that regions that are rapidly developing will continue to close the per capita income gap with developed nations and approach parity with the presently developed world over the course of the next century. Those presently growing less rapidly are assumed to begin the process of more rapid development some time during the next century. The technical efficiency and cost performance of existing energy technologies is assumed to continue improving over time. For example, fossil fuel powerplants are assumed to reach an efficiency level of 66% by 2050 and the cost of solar electricity is assumed to reach 10 c/kWh in 2035, and decreases by 1% per year thereafter. We also assume that end-use energy intensities decline in all regions.

MODELING CARBON CAPTURE AND SEQUESTARATION TECHNOLOGIES

In order to model the cost and performance of the carbon capture and sequestration technologies within the MiniCAM, we have decomposed these costs into three categories and made assumptions about how these technologies will perform over time.

[1] There are a few exceptions. Consideration was given to the problem more than a decade ago, see Steinberg et al. 1984. This investigation was path breaking, but dealt with a limited set of technology options, which were not embedded in an energy-economic framework. More recently a few analysts such as Mori (1998) have considered the problem of introducing carbon capture and sequestration into energy system models, but this paper represents the first time that a fully integrated model of energy, economy, agriculture, land-use, and atmosphere has been used to evaluate the energy and economic implications of carbon capture and sequestration technologies in a program of atmospheric stabilization.

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The Parasitic Energy Costs of Capturing CO_2: The capture of CO_2 from the waste stream of a plant requires energy. We assume that the efficiency of carbon capture will increase with time, i.e., new and improved technologies and processes will come on-line that will reduce the energy penalty associated with powering the capture systems. Herzog, et. al. (1997) state that the eventual integration of these systems into the overall design of new fossil fueled power plants –such as integrated gasification combined cycle (IGCC) power plants– holds forth the promise of reducing the cost of CO_2 capture significantly. Further, recent research indicates that targeted basic science programs could lead to advancements that over time would improve the performance and reduce the costs of these systems (Dooley and Edmonds 1997). We will assume that the phasing in of these more efficient capture technologies will occur gradually and will be completed 50 years after the initiation of carbon capture.

Additional Capital Costs for the Carbon Capture System: We base our assumptions for the additional capital investment needed for the CO_2 capture system largely on the work of on Gottlicher and Pruschek (1997) and their comprehensive survey of over 300 studies of CO_2 removal systems from fossil-fueled power plants. Gottlicher and Pruschek's estimates of the performance of these CO_2 removal systems is based on the "present status of the technology," and therefore we will once again adopt the same assumption about costs decreasing over time. Given the wide range of cost reported by Gottlicher and Pruschek (1997) we adopt a midrange cost from their survey.

CO_2 Transport Costs: For the foreseeable future, the vast majority of research for disposal applications is likely to be focused on understanding and mitigating environmental concerns that arise from disposal and is unlikely to be directed at reducing the cost of disposal (Freund and Ormerod, 1997). Freund and Ormerod (1997) site estimates for transport and disposal cost that range from $4.7/ ton of C to $21/ ton of C depending upon whether the sequestration is to take place in a nearby depleted oil and gas well or a deep sea trench that is located some distance from an on-shore fossil-fueled power plant. In the absence of research that pairs current and future power plant sites with disposal sites on a global basis, we will assume an intermediate value of $15/ tonne C for all transport and disposal costs and hold this cost constant through out the time period under study.

CO_2 will also need to be captured from fuel conversion facilities such as plants for the conversion of coal to synthetic liquids and gases. Herzog, et. al. (1997) state that the cost of CO_2 capture from refineries will be comparable to or greater than the cost of capture from fossil fueled power plants. Therefore, we assume that all conversion facilities and refineries will have performance characteristics similar to those for coal-fired plants. We summarize our assumptions for capture and disposal in Table 1. The figures in Table 1 are not representative of any given capture and sequestration system configuration but rather are meant to be averages for the entire suite of carbon capture and disposal technologies and systems that could be deployed in any number of possible combinations.

Table 1. Assumed Cost and Performance of Carbon Capture and Disposal[2]

	Coal	Oil and Gas
Energy Penalty for Carbon Capture [(a)]	37% declining to 9%	24% declining to 10%
Additional Investment Costs for Capture System [(b)]	54% declining to 33%	54% declining to 33%
Transport and Disposal Cost [(c)]	$15/tonne of C	$15/tonne of C
Efficiency of Capture [(b)]	90%	90%

Sources: [(a)] Herzog, et. al. 1997, [(b)] Gottlicher and Pruschek, 1997, [(c)] Freund and Ormerod, 1997

TWO FUTURE GLOBAL ENERGY SECENARIOS

Carbon capture and sequestration technologies are never used in reference scenarios. The market for CO_2 cannot support large-scale deployment of these technologies. The potential value of these technologies lies in cases in which active intervention to control emissions occur. We consider two qualitatively different policy intervention scenarios of future energy and greenhouse gas emissions scenarios which achieve the ultimate objective of the Framework Convention on Climate Change (FCCC), stabilization of greenhouse gases and compare them to the

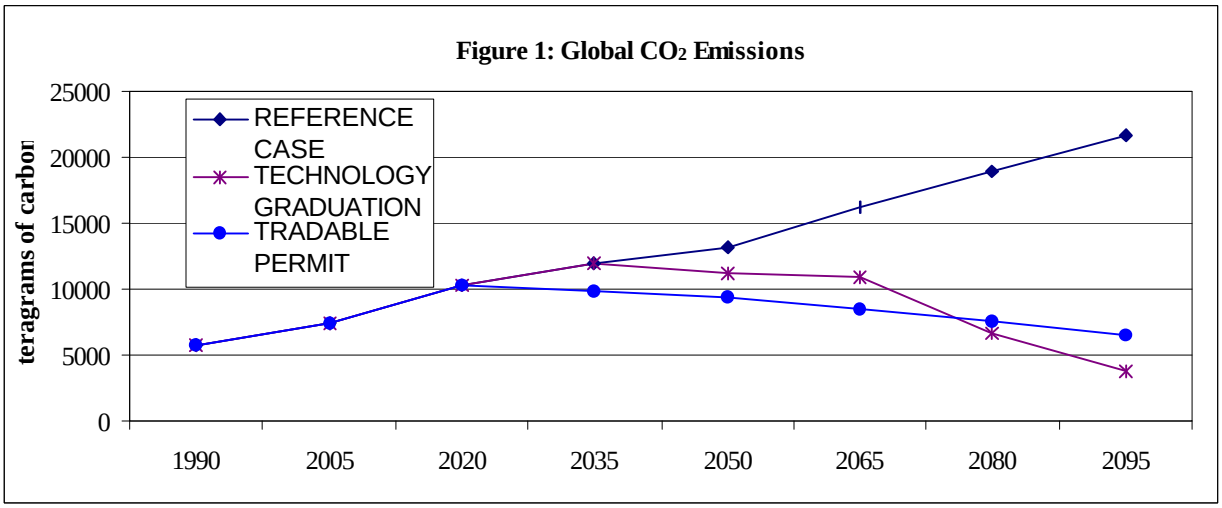
[2] We note that the figures listed here for "Energy Penalty for Carbon Capture" and "Additional Investment Costs for Capture System" are largely consistent with midrange estimates for these parameters published by the IEA Greenhouse Gas Programme (1996).

MiniCAM's Reference Case scenario. The first of the constructed climate-policy scenarios is a technology protocol that mandates any new Organization for Economic Cooperation and Development (OECD) electric power capacity and synthetic fuels capacity added after 2035 be carbon neutral. That is, net carbon emissions from these activities must be zero.[3] This protocol also has a graduation clause that mandates that non-OECD nations will undertake the same obligations that OECD nations undertake when their per capita income, measured by purchasing power parity, equals 50% of the average, year-2035 OECD per capita income. We will refer to this scenario as the Technology Graduation case. It is important to note that the Technology Graduation case is not intended to achieve a specific reduction in emissions per year or to achieve the stabilization of atmospheric concentrations of CO_2 at any predetermined level. Rather, once the protocol is engaged all CO_2 from new fossil-fueled capacity is captured and sequestered; the protocol is never "turned-off" or modified. While we have not constrained emissions directly, we have chose the initiation date such that the case leads to a stabilization of the concentration of atmospheric carbon at approximately 550 ppmv.

We compare this to an alternative implementation approach, which will be referred to as the Tradable Permit case. In this case, we examine the role played by carbon capture and sequestration in a future in which carbon emissions are reduced in a global regime of tradable permits in which all nations participate. We also have constructed this case so that atmospheric concentrations of CO_2 are stabilized at the end of the next century at 550 ppmv, which is roughly twice the pre-industrial concentration of CO_2. This case minimizes the cost of meeting any emission level in any period. We constrain global emissions to the path prescribed for the 550 ppmv ceiling as defined by Wigley et al. (1996).

CARBON CAPTURE/SEQUESTRATION AND ATMOSPHERIC STABILIZATION

Figure 1, shows annual global CO_2 emissions for the Reference case, the Technology Graduation case, and Tradable Permit case. Global emissions in Reference (a business as usual case) are still rapidly rising at the end of the century. Reference emissions in 2095 are 21,683 teragrams of carbon (TgC), which equates to an atmospheric concentration of 722 ppmv at the end of the century. The Tradable Permit case is initiated in 2020. This protocol has 2095 emissions of 6,556 TgC, which equates to end of century atmospheric concentration of 528 ppmv. The Technology Graduation protocol is initiated in 2035 and it has emissions of 3,713 TgC in 2059, which equates to an atmospheric CO_2 concentration of 540 ppmv at the end of the next century. Both cases also reduce peak annual emissions significantly when compared to the Reference case's peak emissions of 21,684 TgC which occur in 2995. Emissions peak in 2035 at 12,023 TgC in the Technology Graduation case and in 2020 at 10,324 TgC in the Tradable Permit case.



Figures 2 and 3 respectively show the amount of carbon needing to be sequestered on a regional basis to achieve the emissions reductions in the Technology Graduation and the Tradable Permit cases. Figure 2 clearly shows the

[3] This could be accomplished either by utilizing a technology, which has no net carbon release such as hydro, nuclear, or solar electric, or biomass, or by capturing and sequestering carbon. The concept could be extended to include offsetting activities such as energy conservation, or emissions mitigation in non-participating regions.

workings of the Technology Graduation case's graduation function. By 2035, the first year the protocol enters into effect China has already attained a GDP per capita that satisfies the graduation clause and therefore China joins the protocol at the outset. Eastern Europe, the Former Soviet Union, and Latin America graduate into the protocol in 2050, while the Mideast and South East Asia graduate in 2065. Africa is the last region to obtain this economic threshold and it graduates into the protocol towards the end of the century in 2080. Figure 3 shows that the market based mechanism of the Tradable Permit results in a small amount of carbon being sequestered in all regions from the outset.

Figure 2: Regional Carbon Sequestration Loads for TECHNOLOGY GRADUATION

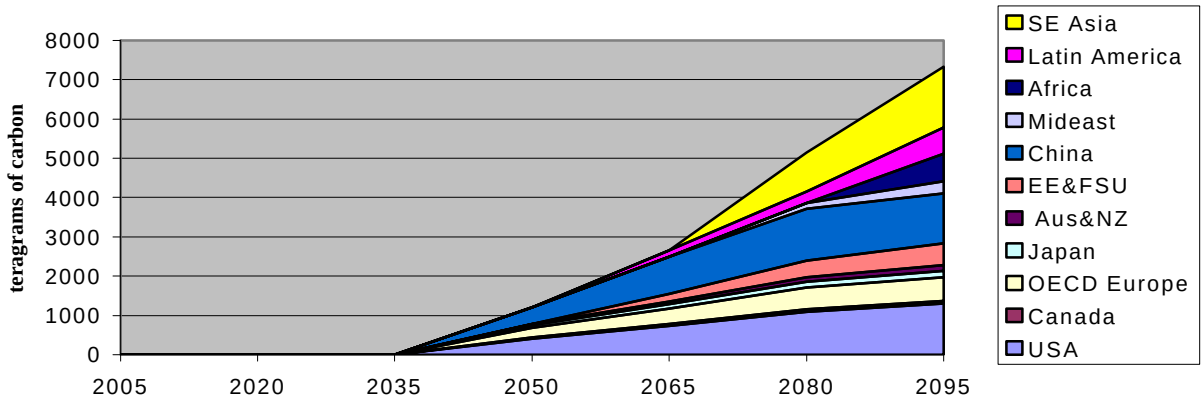
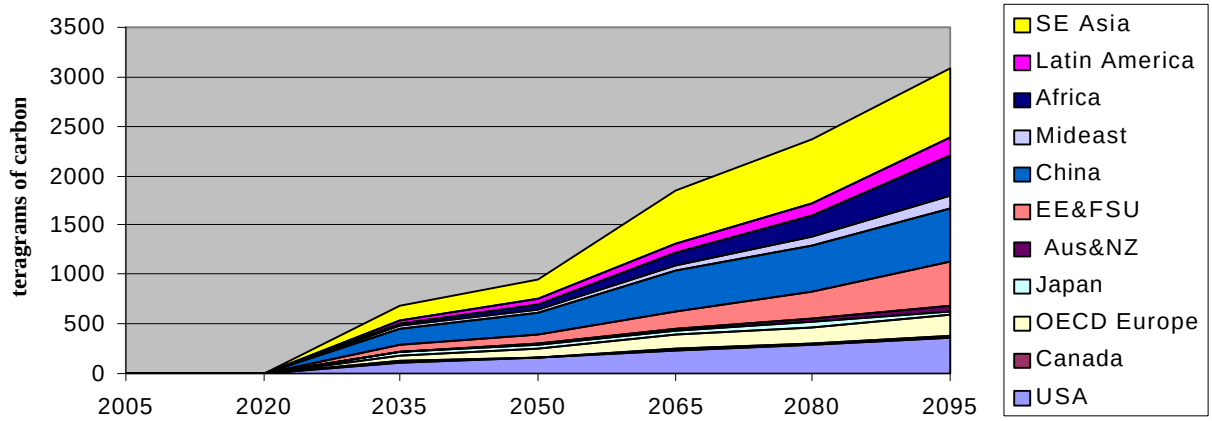


Figure 3: Regional Carbon Sequestration Loads for TRADABLE PERMIT



In terms of the amount of carbon needing to be sequestered, the difference between the two protocols is dramatic. The Technology Graduation case requires up to 2.4 times (7,326 TgC vs. 3,083 TgC) as much carbon be sequestered annually on a global basis by 2095. Not only is there less carbon to be sequestered in the Tradable Permit case, but the amount needing to be sequestered is also spatially more evenly distributed than in the Technology Graduation case. For example, in the Technology Graduation case where there is no global emission trading system, the OECD countries account for over 50% of the global carbon sequestration loads in the middle of the next century (2035 to 2065), while in Tradable Permit these countries account for less than a third (32%) of global carbon sequestration in this same time period.

The carbon needing to be sequestered in the Tradable Permit case is also better distributed with respect to time, with only 37% of the cumulative carbon being sequestered in the last time frame (2080-2095). However in the Technology Graduation case nearly half (49%) of the cumulative carbon must be sequestered in this last 15 year time period. By the end of the next century, the Technology Graduation case will have sequestered a cumulative total of 190,039 TgC, while the Tradable Permit case will require 110,816 TgC to be sequestered. These figures should be compared to the estimates of CO_2 sequestration capacity for some of the more prominent reservoirs displayed in Table 2. The Technology Graduation case and the Tradable Permit case cumulative totals exceed some of the low-end storage capacities estimated by Herzog, et. al.

Table 2: Estimates of Global Carbon Storage Reservoirs (Herzog et al. 1997)

	Range (TgC)	
Carbon Storage Reservoir	**Low**	**High**
Deep Ocean	1,391,000	27,000,000
Deep Aquifers	87,000	2,727,000
Depleted Gas Reservoirs	136,000	300,000
Depleted Oil Reservoirs	41,000	191,000

We have computed the cost for the Tradable Permit case of stabilizing atmospheric concentrations of CO_2 at 550 ppmv to be approximately 1.56% of world gross domestic product. While this is a significant sum, without these carbon capture and sequestration technologies (even assuming the same efficient implementation of the mitigation strategy), the cost of stabilizing the atmosphere at this same level would rise to 2.42% of world GDP.

CONCLUSION

We have shown that carbon capture and sequestration technologies can play a very powerful role in controlling atmospheric concentrations of CO_2. Moreover, when these technologies are coupled with an efficient emission trading regime they will be a key component of efforts to economically stabilize atmospheric concentrations of CO_2.

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REFERENCES

Dooley, JJ and Edmonds, JA. "Workshop for the Preliminary Identification Of Basic Science Needs and Opportunities for the Safe and Economical Capture and Sequestration of CO_2". Published in Benson, S, W Chandler, J Edmonds, M Levine, L Bates, H Chum, J Dooley, D Grether, J Houghton, J Logan, G Wiltsee, L Wright. *Carbon Management: Assessment of Fundamental Research Needs*. US Department of Energy, Office of Energy Research. Washington, DC. August 1998.

Edmonds, J., and M. Wise. 1998. "Building Backstop Technologies And Policies To Implement The Framework Convention On Climate Change," *Energy & Environment.* 9(4):383-397.

Edmonds, J., M. Wise, H. Pitcher, R. Richels, T. Wigley, and C. MacCracken. 1998. "An Integrated Assessment of Climate Change and the Accelerated Introduction of Advanced Energy Technologies: An Application of MiniCAM 1.0," *Environmental Modelling & Assessment*, (forthcoming).

Edmonds, J., M. Wise, R. Sands, R. Brown, and H. Kheshgi. 1996. *Agriculture, Land-Use, and Commercial Biomass Energy: A Preliminary Integrated Analysis of the Potential Role of Biomass Energy for Reducing Future Greenhouse Related Emissions*. PNNL-11155. Pacific Northwest National Laboratories, Washington, DC.

Freund, P and Ormerod, WG. 1997. "Progress Toward Storage of Carbon Dioxide." Energy Conversion and Management. Volume 38, Supplement. pp. S199-S204.

Gottlicher, G and Pruschek, R. 1997. "Comparison of CO_2 Removal Systems for Fossil-Fuelled Power Plant Processes." Energy Conversion and Management. Volume 38, Supplement. pp. S173-S178.

Herzog, H., E. Drake, and E. Adams. 1997. *CO_2 Capture, Reuse, and Storage Technologies for Mitigation Global Climate Change*. Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

IPCC (Intergovernmental Panel on Climate Change), 1996a. *Climate Change 1995: The Science of Climate Change. The Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. J.P. Houghton, L.G. Meira Filho, B.A. Callendar, A. Kattenberg, and K. Maskell (eds.). Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 1996b. *Climate Change 1995: Economic and Social Dimensions of Climate Change. The Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. J.P. Bruce, H. Lee, and E.F. Haites (eds.). Cambridge University Press, Cambridge, UK.

International Energy Agency (IEA). 1996. *Carbon Dioxide Capture from Power Stations*. IEA Greenhouse Gas R&D Programme. Cheltenham, United Kingdom..

Mori, S. 1998. "An Integrated Assessment Model for the Evaluation of New Energy Technologies and Food Productivity", *International Journal of Global Energy Issues*, (1998, in printing).

Steinberg, M., Cheng, H.C., and Horn, F. 1984. *A Systems Study for the Removal, Recovery, and Disposal of Carbon Dioxide from Fossil Fuel Power Plants in the U.S.*, DOE/CH/00016-2, U.S. Department of Energy, Washington, D.C.

UNFCCC [United Nations Framework Convention on Climate Change]. 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 10, 1997. Kyoto, Japan.

Wigley, T.M.L., R. Richels & J. A. Edmonds. 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature*. 379(6562):240-243.