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**The Symbiosis of Carbon-Dioxide Sequestration and Hydrogen Fuel: What is its Significance
for the Long-Term Global Energy System?**

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ABSTRACT

Recently, it has been proposed that hydrogen fuel could be produced thermochemically from fossil sources (for example by steam reforming of natural gas or gasification of coal), with low cost capture and sequestration of byproduct CO₂. This opens the possibility of continued use of fossil derived fuels for applications such as transportation, with greatly reduced emissions of CO₂ to the atmosphere. This "fuel decarbonization/CO₂ sequestration" strategy represents an alternative to increased reliance on either nuclear power or renewables to achieve CO₂ emission reduction goals.

OBJECTIVES

Over the past two and a half years, we have conducted a multi-dimensional examination of the implications of the "fuel decarbonization/carbon sequestration" strategy for the world energy system. Objectives of the research are:

- * Understand the most promising configurations for hydrogen energy systems with carbon sequestration,
- * Make this strategy better known and readily accessible for use in the next generation of integrated assessment models.

APPROACH

Technical and economic assessments of hydrogen energy systems with CO₂ sequestration were carried out for a variety of systems.

- * Production of hydrogen from coal bed methane with sequestration of CO₂ in the coal bed.

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- * Processes for co-producing hydrogen and electricity from coal, using high temperature membrane hydrogen separation systems.
- * Assessment of strategies for developing a hydrogen energy system with CO₂ sequestration.

To communicate these results, a series of papers and presentations were made to diverse audiences (see below). In addition, we held numerous discussions with researchers in the integrated assessment community.

We have contributed to development of energy R&D strategies, incorporating these ideas, through our participation in several high level government panels and working groups.

RESULTS

Publications and Presentations

To reach a wide variety of audiences in the energy community, a series of papers were presented, and several publications appeared or are in press. (Our publications on carbon sequestration and hydrogen energy for the period July 1998-July 2000 are listed on the attached page.)

References 1-7 are technical papers directed primarily to researchers in the integrated assessment, climate change, energy and hydrogen research communities. References 8-17 are written for a more general audience, including decision makers in government and industry. References 18-19 are presentations to key audiences in government and in the energy industries.

In addition to these papers, we have contributed to several important studies

- * Socolow and Ogden made significant contributions to the 1999 DOE Roadmap for Carbon Sequestration. Both served as active members of the "cross-cutting" committee, and helped write portions of Chapters 1 and 2 of the report.
- * Socolow is serving as a member of the NRC Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes, which, as part of its review of Vision 21, is looking at the place of carbon sequestration in the R&D supported by the Division of Fossil Energy of the US Department of Energy.
- Williams was heavily involved in writing the 1997 PCAST report on US Energy R&D Needs in the 21st Century, and also served as a member of the PCAST panel which released a report in June 1999 on energy R&D designed to meet international objectives. Both reports highlighted carbon sequestration as a potentially important energy technology for the 21st century.
- Williams served as lead author of the Advanced Energy Supply Technology chapter of the recently published World Energy Assessment. This work addressed the importance of advanced fossil energy complexes incorporating CO₂ sequestration in meeting future energy supply goals.
- Socolow was co-author of a December 1999 DOE report on *Carbon Sequestration Research and Development*

- In January-March 2000, Ogden and Socolow served on a DOE panel evaluating DOE's Energy R&D Portfolio. The potential roles of hydrogen and carbon sequestration in meeting future national energy goals were among many topics discussed. The PCAST 1997 and 1999 reports above were used as background documents for the evaluation.
- Socolow was co-author of a National Academy study on the future of the Vision 21 program.

Impacts of our work in the Integrated Assessment Community. The idea of fuel decarbonization/carbon sequestration is rapidly becoming part of the toolkit of integrated assessment modelers. For example, in a recent paper presented at the May meeting of the International Petroleum Industry Environmental Conservation Association, (entitled "The Global Energy Strategy to Address Climate Change") John Clarke and Jae Edmonds used their integrated assessment model to estimate that in 2095 almost 5 Gigatonnes of Carbon per year could be saved via hydrogen production with sequestration. DOE support has allowed our group to develop these ideas and present them to diverse audiences. In the past two years, Princeton, with DOE support, has put the fuel decarbonization/carbon sequestration strategy "on the map" of carbon management for both the public and private sector.

Impacts of our work in the Energy Industries.

CEES studies of carbon sequestration have found a receptive audience in the energy industries. Socolow, Ogden and Williams have given numerous presentations to researchers and decision makers in the oil industry over the past two years. This fall researchers at CEES led by Socolow and Williams will begin collaboration with BP Amoco under a new Carbon Mitigation Initiative program. This program will incorporate studies of CO₂ sequestration.

PUBLICATIONS AND PRESENTATIONS BASED ON OUR DOE SUPPORTED RESEARCH (July 1998-July 2000)

- 1) R.H. Williams, "Hydrogen from Coal and Coal Bed Methane, Using Byproduct CO₂ for Enhanced Methane Recovery, with CO₂ Sequestration in the Coal Bed," Princeton University, Center for Energy and Environmental Studies Report No. 309, August 1998.
- 2) R.H. Williams, "Hydrogen from Coal and Coal Bed Methane, Using Byproduct CO₂ for Enhanced Methane Recovery, with CO₂ Sequestration in the Coal Bed," prepared for the 4th International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland, 30 August - 2 September 1998.
- 3) R.H. Williams, "Some Possibilities for and Implications of Successful Development of Advanced Technologies for Making Low Cost Hydrogen from Coal," viewgraphs from presentation to the Committee on R&D Opportunities for Advanced Fossil Fueled Energy, National Research Council, Washington DC, 31 March 1999.
- 4) R.H. Williams, 1999, "Hydrogen Production from Coal and Coal Bed Methane, Using Byproduct CO₂ for Enhanced Methane Recovery and Sequestering the CO₂ in the Coal Bed," *Proceedings of the 4th International Conference on GHG Control Technologies*, B. Eliasson, P. Riemer, and A. Wokaun, eds., Pergamon, Amsterdam, pp. 799-804.4)
- 5) J. Ogden, 1999, "Prospects for Building a Hydrogen Energy Infrastructure," *Annual Review of Energy and the Environment*, Vol. 24, pp. 227-279.
- 6) J. Ogden, "Strategies for Developing Hydrogen Energy Systems with CO₂ Sequestration," *Proceedings of the 10th National Hydrogen Association Meeting*, Vienna, VA, April 7-9, 1999.
- 7) Williams, R.H., 1999: "Toward Zero Emissions for Coal: Roles for Inorganic Membranes," in *Proceedings of the International Symposium Toward Zero Emissions: the Challenge for Hydrocarbons*, EniTecnologie, Rome, Italy, 11-13 March, pp. 212-242.
- 8) R.H. Williams, "A Technological Strategy for Making Fossil Fuels Environment and Climate Friendly," *World Energy Council Journal*, pp. 59-67, July 1998.
- 9) J. M. Ogden, "Hydrogen: A Low Polluting Energy Carrier for the Next Century," *Pollution Prevention Review*, John Wiley and Sons, pp. 11-22, Autumn 1998.
- 10) M. M. Steinbugler and R.H. Williams, "Beyond Combustion: Fuel Cell Cars for the 21st Century," *Forum for Applied Research and Public Policy*, vol. 13, No. 4, pp. 102-107, Winter 1998.
- 11) R. H. Socolow, "The Role of Fossil Derived Hydrogen in Greenhouse Gas Mitigation," presented at the IPIECA Technology Assessment Workshop, International Petroleum Industry Environmental Conservation Association, Total Head Office, La Defense, Paris, France, May 11-12, 1999.
- 12) S. Benson, J. Edmonds, R. Socolow and T. Surles, "Human Impacts and Management of Carbon Sources," in P. Eisenberger and M. Knotek, ed.s, "Basic Research Needs for

Sustainability: The Carbon Problem," National Science Foundation and US DOE, published by the Biosphere 2 Center, Columbia University, May 1999.

13) Robert H. Socolow, "Nitrogen management and the future of food: Lessons from the management of energy and carbon," *Proc. Natl. Acad. Sci. USA*, Vol. 96, pp. 6001-6008, May 1999.

14) Robert H. Socolow, *Vision 21: Fossil Fuel Options for the Future* (contributor), Board on Energy and Environmental Systems, Washington, D.C.: National Academy Press, 2000.

15) Robert H. Socolow, Co-author, *Carbon Sequestration Research and Development*, Dave Reichle, John Houghton, Bob Kane, Jim Eckmann, et al. (20 authors), A U.S. Department of Energy Report, Office of Science and Office of Fossil Energy, DOE/SC/FE-1, December 1999, web address: www.ornl.gov/carbon_sequestration.

16) Robert H. Socolow, *Global Change Ecosystems Research* (contributor), Ecosystems Panel, Oversight Group for the Ecosystems Panel, Washington, D.C.: National Academy Press, 2000.

17) Williams, R.H. (Convening Lead Author) and Contributing Authors Matthew Bunn (U.S.), Stefano Consonni (Italy), William Gunter (Canada), Sam Holloway (U.K.), Robert Moore (U.S.), and Dale Simbeck (U.S.), "Chapter 8: Advanced Energy Supply Technologies," *World Energy Assessment*, in the press

18) J.M. Ogden, "Building a Hydrogen Energy Infrastructure," invited presentation to the USDOE Lab Directors LERDWG group, Washington, DC, November 10, 1999.

19) J. Ogden, "Prospects for Development of Hydrogen as an Energy Carrier," invited presentation at the Energy Frontiers International Green Technologies Meeting (an annual meeting of oil, gas and energy industry decision makers), Marco Island, FL, Jan.31-Feb 2, 2000.