Reprinted from the *World Energy Council Journal*, July 1998

A Technological Strategy for Making Fossil Fuels Environment- and Climate-Friendly

Robert H. Williams
Center for Energy and Environmental Studies
Princeton University

It is becoming more and more difficult to meet increasingly stringent air quality goals by mandating the use of ever tighter "end-of-pipe" pollution emission controls on fossil energy conversion devices. Regulatory end-of-pipe emission control strategies are also not well suited for the many parts of the world where air quality is rapidly deteriorating and environmental regulatory infrastructures are not well developed.

Moreover, many believe that addressing climate change risks will require substantial reductions in fossil fuel use during the course of the next century, so that much of the world's requirements for energy in the next century will be met by non-fossil-energy sources.

Although there are good prospects that various renewable energy technologies can come to play major roles in the global energy economy in the next century (Reddy, Williams, and Johansson, 1997), there are also emerging new technologies that might make it possible to use fossil fuels with near-zero emissions of both local and regional air pollutants and greenhouse gases-without significantly increasing energy costs. This paper discusses one especially promising class of such technologies: fuel cells for transportation, stationary power generation, and combined heat and power (CHP) generation used with hydrogen obtained from decarbonization of fossil fuels in conjunction with geological storage of the separated CO_2. The paper argues that successful commercialization of fuel cells would help propel a shift to hydrogen as an energy carrier, and that fossil fuels would have large roles in providing the needed hydrogen even in a severely greenhouse gas emissions-constrained world.

Background on Fuel Cells

The fuel cell was discovered and demonstrated in 1839 by Sir William Grove, a British lawyer and judge. After a long dormancy period the technology was "rediscovered" for space applications in the 1960s. Recent interest in earth-bound applications has been stimulated both by concerns about air pollution and climate change posed by conventional fossil fuel technologies and by recent technological advances indicating that fuel cell technologies have good prospects for becoming widely competitive, especially in a world where environmental concern is an effective driver for energy technological innovation.

Reproduced with permission from World Energy Council

The fuel cell is a device that converts the chemical energy of fuel directly into electricity without first burning the fuel to produce heat (Kartha and Grimes, 1994). Electricity is produced at high efficiency with little or no pollutant emissions-without the need for end-of-pipe emission control technologies. All practical fuel cells are fueled by hydrogen (H2). The fuel delivered to the fuel cell can be either H2 or an energy carrier such as a hydrocarbon or alcohol fuel that is processed at the point of use into a H2-rich gas that the fuel cell can use.

Fuel cell systems are less capital intensive, more-energy-efficient, and require less maintenance if the energy carrier that serves them is H2. Thus fuel cells "prefer" to be fueled with H2 and put a high market value on H2 as an energy carrier.

Hydrogen Safety

Safety is a concern that must be satisfactorily addressed before H2 can be widely used as an energy carrier. Despite its inherent cleanliness, hydrogen is widely perceived as being an "unsafe" fuel. All fuels are inherently dangerous and become "safe" only if properly managed. A major study on H2 safety carried out at the Sandia National Laboratories (Ringland, 1994) concluded that: "There is abundant evidence that H2 can be handled safely, if its unique properties-sometimes better, sometimes worse, and sometimes just different from other fuels-are respected."

Hydrogen Production and CO_2 Sequestration Technology

Although H2 is not used as an energy carrier, it is a common chemical feedstock, used mainly in the chemical industry (mostly for making ammonia) and in petroleum refining; about 1% of U.S. primary energy is converted to H2 for such applications; there are about 1200 km of H2 pipelines in the world-mainly in the United State, Germany, the Netherlands, and Great Britain. Technologies for H2 manufacture are well-established. The dominant commercial technology is via steam reforming of natural gas; it can also be made via gasification of coal or any other carbonaceous feedstock (Williams et al., 1995) or via electrolysis of water using renewable or other power sources. Until fossil fuel prices are much higher than at present, electrolytic H2 will be much more costly than fossil fuel-derived H2 (Williams, 1998a), except where low-cost offpeak hydroelectric power is available-supplies of which are very limited.

When H2 is made from a carbonaceous feedstock, an intermediate product is a gaseous mixture consisting mainly of CO_2 and H2, from which the H2 must be separated by a chemical or physical process. Relatively minor process changes can be made to recover the CO_2 as a relatively pure stream instead of venting it to the atmosphere. The recovered CO_2 can then be compressed and transported by pipeline as a dense supercritical fluid to where it can be stored in isolation from the atmosphere. If the H2 is produced in a large, centralized production facility, the cost of separating and sequestering the CO_2 can be relatively modest. It has been estimated that for a large plant (e.g., one large enough to support about 2 million fuel cell cars) these costs would add, with current technology, 23% and 28% to the cost of producing H2 with CO_2 venting, for natural gas and coal feedstocks, respectively, for a case where the CO_2 is stored in a depleted natural gas field some 70 km from the H2 production site. This cost penalty is much less than the 50-75% cost penalty associated with CO_2 recovery and sequestration for a natural gas or coal electric plant (Kaarstad and Audus, 1997).

Both the costs of making H2 from fossil fuels and cost penalties associated with CO_2 recovery and sequestration will undoubtedly be reduced with advanced technology. One promising option involves use of an inorganic ceramic membrane to separate H2 from CO_2 and other fuel gases at high temperatures; this technology offers the promise of substantial increases in efficiency and reductions of capital costs for H2 production; the membranes can be manufactured via processes similar to well-established technology for making membranes for gaseous diffusion uranium enrichment (Parsons I&TG, 1998). Another promising, low-cost approach for separating CO_2 and H2 involves bubbling the gaseous mixture through a chilled, pressurized water column; the H2 passes freely but the CO_2 become trapped in CO_2 clathrate hydrate crystals that are formed in the process, and from which pressurized gaseous CO_2 can subsequently be recovered and compressed moderately for transport and ultimate disposal (Spenser and White, 1998).

The Prospects and Potential for Sequestering CO_2

Although disposal in the deep oceans has been the most-discussed option for CO_2 disposal, much more research is needed to better understand the security of various ocean disposal schemes and their environmental impacts (Turkenburg, 1992). In recent years increasing attention has been given to geological (underground) storage of CO_2: in depleted oil and natural gas fields (including storage in conjunction with enhanced oil and gas recovery), in deep saline aquifers, and in deep coal beds [in conjunction with coal bed methane (CBM) recovery].

Sequestration in depleted oil and gas fields is generally thought to be a secure option if the original reservoir pressure is not exceeded. One estimate of the prospective sequestering capacity of oil and gas reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources (most of which will be used up during the next century) is about 100 GtC for oil fields and about 400 GtC for natural gas fields (Hendriks, 1994); other estimates of the oil and gas field sequestering capacity are as low as 40 GtC for depleted oil fields plus 20 GtC associated with enhanced oil recovery plus 90 GtC for depleted natural gas fields (IPCC, 1996). (For comparison, global CO_2 emissions from fossil fuel burning totaled 6 GtC in 1990.) There is a considerable range of uncertainty in the global sequestering capacity of depleted oil and gas fields and the security of such sequestration. More research and field testing are needed to refine sequestering capacity estimates, because reservoir properties vary greatly in their suitability for storage, and because the recovery of oil and gas from these reservoirs may have altered the formations and affected reservoir integrity. Much of the prospective sequestering capacity will not be available until these fields are nearly depleted of oil and gas.

An important characteristic of systems that produce H2 from fossil fuels will be low-cost byproduct CO_2. Thus CO_2 injection for enhanced oil recovery (EOR, which is established technology), enhanced natural gas recovery (Blok et al., 1997), or CBM recovery [a new technology that could be commercial in less than a decade (Gunter et al., 1997)] are likely to become foci of initial efforts to sequester this CO_2 in profitable ways.

An example of an EOR application is the recently announced plan by Norsk Hydro to build a large combined cycle power plant to be fueled with H2 derived from natural gas via steam reforming and to inject the separated CO_2 into the Grane oil field on the Norwegian continental shelf, for EOR as well as for CO_2 sequestration.

An opportunity related to CBM recovery in China would be to site near deep CBM deposits some of the many planned facilities for making ammonia from H2 manufactured from coal using modern coal gasifiers (Williams, 1998b). Such plants produce large quantities of byproduct CO_2 that could be used for CBM recovery. Although most countries make ammonia from natural gas, China also makes it from coal, since its conventional natural gas resources are limited. But China has large CBM deposits, from which methane recovery via CO_2 injection is likely to be economically interesting if low cost sources of CO_2 are available. China's use of coal as a feedstock for ammonia production offers the advantages that much more byproduct CO_2 is available per unit of ammonia produced, at a lower cost per tonne of CO_2 than is possible when ammonia is made from natural gas; the recovered methane could be used to make more H2 and thus more ammonia, at lower cost that with coal only. In the future, China could use this same strategy to make H2 from coal plus CBM with very low lifecycle CO_2 emissions for use in fuel cells in both transportation and stationary power and CHP markets, if and when fuel cells are established in Chinese markets.

Without the benefit of credits for enhanced resource recovery, storage in aquifers will generally be somewhat more costly. However, aquifers are much more widely available than oil or gas fields or CBM reservoirs; they underlie most sedimentary basins, which account for nearly half of the land area of the inhabited continents. To achieve high storage densities, CO_2 should be stored at supercritical pressures (i.e., at pressures in excess of 74 bar). Since the normal hydrostatic geopressure gradient is about 100 bar per km, typically depths of about 800 m or more are desirable for sequestering CO_2 in aquifers. The aquifers at such depths are typically saline and not connected to the much shallower "sweetwater" aquifers used by people.

If aquifer storage must be restricted to closed aquifers with structural traps, the potential global sequestering capacity is relatively modest-some 50 GtC (Hendriks, 1994), equivalent to less than 10 years of global CO_2 production from fossil fuel burning at the current rate. However, if structural traps are not required for secure storage, the storage capacity of aquifers might be huge(some 14,000 GtC (Hendriks, 1994), equivalent to more than 2,000 years of CO_2 emissions from fossil fuel burning at the current global rate. A growing body of knowledge indicates that many large horizontal open aquifers might provide secure storage if the CO_2 is injected far from the reservoir boundaries (Holloway, 1996). The notion that large horizontal aquifers can provide secure sequestration is a relatively new idea that has led to an increase in confidence that long-term sequestration of a significant fraction of the next several centuries of global CO_2 production from human activities might be feasible (Socolow, 1997).

Good estimates of the aquifer sequestration potential require considerable data gathering for and detailed modeling of specific aquifers. A recent major study carried out under the Joule II Non-Nuclear Energy Research Programme of the European Commission (Holloway, 1996) did a considerable amount of such modeling in an assessment of underground CO_2 storage reservoirs in Europe. This study estimated that the underground storage capacity accessible to the European Union plus Norway (mostly deep aquifers under the North Sea) would be adequate to store more than 200 GtC-storage capacity equivalent to 250 years of CO_2 emissions from all of OECD Europe at the current emission rate.

Experience with aquifer disposal will be provided by two projects involving injection into nearby aquifers of CO_2 separated from natural gas recovered from CO_2-rich gas reservoirs. One is a Statoil project begun in 1996 to recover 1 million tonnes of CO_2 per year from the Sleipner Vest offshore natural gas field in Norway (Kaarstad, 1992). The second, which will commence in about a decade, will involve the recovery of over 100 million tonnes per year (equivalent to about 0.5 percent of total global emissions from fossil fuel burning) from the Natuna natural gas field in the South China Sea (71% of the reservoir gas is CO_2) (IEA, 1996).

Evolving Toward Widespread Use of Fuel Cells

How soon will fuel cells begin to make substantial inroads into energy markets? At present only the phosphoric acid fuel cell is being marketed commercially-largely for stationary CHP markets in commercial and residential apartment buildings. Power densities achievable with this technology are too low for it to be used in cars, and high costs might limit its overall market potential.

The technology currently getting the most attention is the proton exchange membrane (PEM) fuel cell, which operates at a low temperature (~ 80 oC) and offers both a high power density (suitable for use in cars) and a prospective cost in mass production that might enable the PEM fuel cell electric vehicle (FCEV) to compete with the internal combustion engine vehicle (ICEV) in automotive applications. Over the next two or three years this technology is expected to be commercially available for both transit bus and buildings CHP applications.

Activities relating to PEM FCEV development are expanding rapidly (see Box); most major auto manufacturers are developing FCEVs. Costs are currently high, and many engineering challenges remain to be resolved before the realization of cost targets that would enable FCEVs to compete with ICEVs, but many companies are evolving strategies to reach such goals. Current costs are not associated with intrinsically high costs for materials or manufacturing techniques; rather they are high largely because most fuel cells purchased today are constructed, almost by hand, as "one-off" demonstrators. For successful demonstrations, developers have relied on tried-and-true designs and materials. Now that the PEM fuel cell is technically proven, there is considerable ongoing activity to push the envelope in improving performance and reducing materials costs. Moreover, manufacturing fuel cells in the high volumes associated with automotive applications is expected to drive costs down several-fold.

In the longer term, a system for H2 production and use in PEM fuel cells might involve centralized H2 production and sequestering of the separated CO_2, with pipeline delivery of the H2 to distributed users (see Figure 1). Because a H2 infrastructure does not yet exist, however, PEM fuel cells will probably be introduced using conventional hydrocarbon fuels or other easily transportable and storable liquid fuels that are converted into a H2-rich gas at the point of use. For example, most car manufacturers are developing onboard fuel processors for use with either gasoline or methanol; and PEM fuel cell systems being developed for CHP markets are being designed for use with natural gas fuel processors. For FCEV applications these are likely to be only transitional strategies, however, because the direct H2 FCEV will probably be

Box: Progress in Developing Motor Vehicles Powered by PEM Fuel Cells

1993	Clinton Administration announces Partnership for a New Generation of Vehicles (PNGV) with U.S. automakers, aimed at introducing by 2004 production-ready prototypes of "cars of the future" that will be three times as fuel efficient as today's cars but will maintain size and performance and cost no more to own and drive
1993	Ballard Power Systems of Vancouver (Canada) introduces proof-of-concept H2 PEM fuel cell bus (with compressed H2 storage)
1995	Daimler-Benz introduces NECAR I, a H2 PEM fuel cell test van (with Ballard fuel cell, compressed H2 storage)
1995	Ballard demonstrates H2 PEM fuel cell bus suitable for commercial use (with compressed H2 storage)
1995	Mazda demonstrates a H2 PEM fuel cell golf cart (with compressed H2 storage)
1996	Daimler-Benz introduces NECAR II, a prototype passenger van equipped with a compact H2-powered fuel cell system developed jointly with Ballard (with compressed H2 storage)
1996	Toyota introduces prototype PEM H2 fuel cell car (with metal hydride storage)
1996-97	Ballard sells several H2 PEM fuel cell buses to cities of Chicago and Vancouver
1997	Ballard and Daimler-Benz form joint venture with $320 million planned investment to develop PEM fuel cell cars, with commercialization targeted for 2005 timeframe
1997	Daimler-Benz introduces NECAR III, a prototype small fuel cell passenger car [with onboard methanol (MeOH) reformer]
1997	Toyota introduces prototype fuel cell passenger car (with onboard MeOH reformer)
1997	Ford joins Daimler-Benz & Ballard in joint venture to commercialize fuel cell cars, bringing planned pooled investment total to $420 million; fuel cell power trains for cars targeted for commercialization in 2004
1998	GM announces it will develop production-ready prototype fuel cell cars by 2004
1998	Chrysler announces it will develop production-ready prototype fuel cell cars by 2004 (with onboard gasoline partial oxidation systems)
1998	Mobil Corporation and Ford Motor Company form a strategic alliance to develop develop a hydrocarbon fuel processor for use in fuel cell vehicles
1998	Mazda joins automotive fuel cell alliance with Ballard, Daimler-Benz, and Ford

preferable to any liquid fuel FCEV with an onboard fuel processor-because of the higher first cost, higher maintenance cost, and lower fuel economy of such vehicles compared to the H2 FCEV (Ogden et al., 1997; Steinbugler and Williams, 1998). The expected lower costs for H2 FCEVs would lead to an internally generated automotive market pressure to shift to H2, as soon as a H2 infrastructure can be put into place. (It remains to be shown whether the same kind of market dynamic is to be expected for CHP applications of PEM fuel cells.) But even in the early days of H2 infrastructure development, CO_2 separation and sequestration might not be economically feasible, if, as seems likely, H2 would be produced initially mainly in distributed configurations (e.g., at refueling stations), at which the costs of sequestration would be high because of scale considerations. Sequestration would tend to be a feasible as a low-cost option mainly when fuel cells are in wide use, so that centralized H2 production is practical and the economies of CO_2 disposal at large scales can be exploited.

Molten carbonate and solid oxide fuel cells are also under development, but at a less frenetic pace than is the case for PEM fuel cells. Because these fuel cells operate at high temperatures (~ 550 to 650 oC for molten carbonate and ~ 1000 oC for solid oxide) applications are likely to be mainly in industrial CHP systems that require high-temperature heat for process use and in central-station configurations that involve hybrid cycles in which the "waste heat" from the fuel cell is used to provide additional electricity in a gas turbine and/or steam turbine "bottoming cycle." Extraordinarily high efficiencies are expected from such hybrid cycles-e.g., one natural gas-fueled solid oxide fuel cell/gas turbine hybrid designed by Electric Power Research Institute analysts is expected to have an overall conversion efficiency of about 75% (Bakker, Cohn, and Goldstein, 1996)-considerably higher than the 60% efficiency expected for the next generation (~ year 2000) gas turbine/steam turbine combined cycle power plant. One possible centralized hybrid system that would use coal as a feedstock is shown in Figure 2. This system that would produce electricity (and possibly H2 for transportation as well) is targeted for development under "Vision 21" at the U.S. Department of Energy (Office of Fossil Energy, 1997); the development goal for this initiative is to produce the electricity at 60-65% efficiency, with little if any pollutant or greenhouse gas emissions, at a cost that is 10% less than the best pulverized

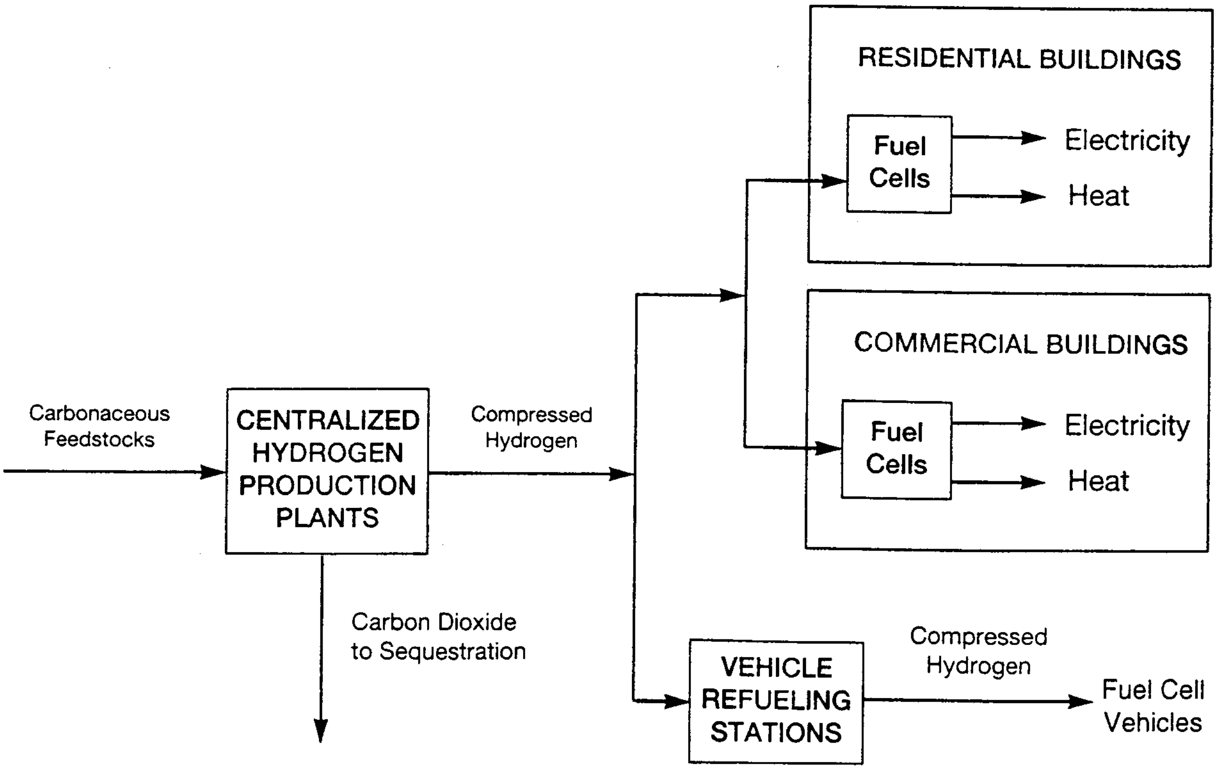

Figure 1. System of Hydrogen Production and Use in Low-Temperature Fuel Cells for Transportation and Distributed Combined Heat and Power Applications.

coal steam-electric power plants on the market today, with possible market entry in the period 2010-2015 (PCAST Energy R&D Panel, 1997). While these are very ambitious energy technology development goals, the performance targets do not violate laws of nature, and the system design is plausible.

Conclusion

The opportunities offered by fuel cells for transportation, CHP, and central-station power generation, and the associated strategy of fossil fuel decarbonization and CO_2 sequestration show that plausibly there is at least one set of technologies for which the phrases "environment- friendly fossil fuels" and "climate-friendly fossil fuels" are not obviously oxymora. Enough is known about these options to warrant their intensive exploration.

This exploration requires that the public and private sectors work together to resolve the major uncertainties. Public sector support for research and development (R&D) is warranted both because the private sector tends to underinvest in R&D generally, and because this class of technologies involves multiple public benefits that are not reflected in market prices of energy. Because energy is a commodity for which margins are inherently thin, temporary public-sector incentives for demonstration and commercialization (D&C) initiatives are also warranted (PCAST Energy R&D Panel, 1997)-incentives which should be crafted to foster rapid progress along learning/experience curves so that technology prices converge quickly to those for conventional energy technologies. For technologies such as fuel cells for which individual units are modular, small in scale, and amenable to the economies of mass production, price is usually well-described as a declining function of the cumulative number of units produced. Thus the cost of "buying down" technology prices to market-clearing levels through D&C incentives should be much less than for large-scale technologies. Indeed, the cumulative investment over a 5-10 year-period for commercializing four different fuel cell technologies for stationary applications in the United States has been estimated to be only US $2 billion (Penner et al., 1995). For comparison, the total global investment in energy at the present time is about US $400 billion per year.

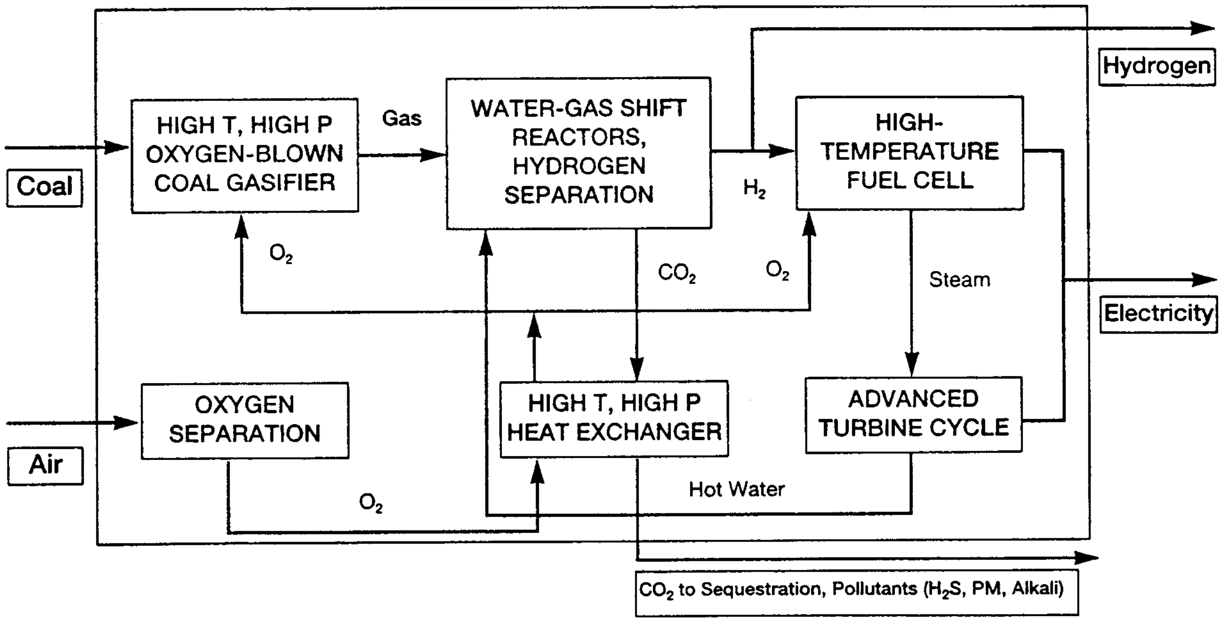

Figure 2. A "Vision 21" Power Plant

This futuristic coal power plant is one design targeted for development under the "Vision 21" initiative at the U.S. Department of Energy (Office of Fossil Energy, 1997). In this system coal is gasified in oxygen via partial oxidation to produce a fuel gas consisting largely of H_2 and CO. This fuel gas is reacted with steam in water- gas shift reactors, the product of which is a gaseous mixture consisting mainly of H_2 and CO_2. The CO_2 is separated out and transported to a storage site where it is isolated from the atmosphere (e.g., in a geological reservoir). The purified H_2 is delivered to a high-temperature H_2/O_2 fuel cell to produce electricity and hot, pressurized steam. The hot, pressurized steam is used to generate extra electricity in an advanced turbine "bottoming cycle." Extra H_2 might also be produced for transmission via pipeline to distributed users (e.g., to refueling stations for H_2 fuel cell electric vehicles-see Figure 1). The goals for "Vision 21" power plants are to produce electricity from coal at 60-65% efficiency, with zero or near-zero emissions of local air pollutants and greenhouse gases, at an electricity generation cost that is 10% less than for today's best pulverized coal steam-electric plants.

Providing public-sector support for such programs will not be easy in light of tightening fiscal conditions and the ongoing secular decline in both public-sector and private-sector investment in long-term energy R&D and D&C in most industrialized countries.
However, even if the ongoing decline in public sector support for energy innnovation cannot be reversed immediately at aggregate levels, the recent Energy R&D Panel Report of the President's Committee of Advisors on Science and Technology found that at the U.S. Department of Energy at least, new R&D programs relating to fossil fuel decarbonization and CO_2 sequestration could be initiated in the near term with resources that could be freed up by phasing out at the Department existing fossil energy R&D programs that offer little promise in dealing with the major climate change and other environmental challenges posed by fossil fuels that will be of paramount importance in the early 21st century (PCAST Energy R&D Panel, 1997).

Public sector investments in R&D and D&C for these technologies are also warranted because resolving cost uncertainties in this area will establish pricing benchmarks for alternative energy technologies that are being developed to cope with climate change and other environmental challenges.

References

Bakker, W., A. Cohn, and R. Goldstein, 1996: Advances in solid-oxide fuel cells. The EPRI Journal, 21 (5), 42-45, September/October.

Blok, K., R.H. Williams, R.E. Katofsky, and C.A. Hendriks, 1997: Hydrogen production from natural gas, sequestration of recovered CO_2 in depleted gas wells and enhanced natural gas recovery. Energy, 22 (2-3), 161-168.

Gunter, W.D., T. Gentzix, B.A. Rottenfusser, and R.J.H. Richardson, 1997: Deep coalbed methane in Alberta, Canada: a fuel resource with the potential of zero greenhouse emissions. Energy Convers. Mgmt., 38 (Suppl.), S217-S222.

Hendriks, C.A., 1994: Carbon Dioxide Removal from Coal-Fired Power Plants. Ph. D. thesis, Department of Science, Technology, and Society, Utrecht University, Utrecht, The Netherlands.

Holloway, S. (British Geological Survey), ed., 1996: The Underground Storage of Carbon Dioxide. Report prepared for the Joule II Programme (DG XII) of the Commission of the European Communities, Contract No. JOU2 CT92-0031, Brussels, February.

IEA (International Energy Agency), 1996: CO_2 capture and storage in the Natuna NG project. Greenhouse Issues, 22, 1.

IPCC (Intergovernmental Panel on Climate Change), 1996: Chapter 19: Energy supply options. In: Climate Change 1995-Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge and New York.

Kaarstad, O., 1992: Emission-free fossil energy from Norway. Energy Convers. Mgmt, 33 (5-8), 781-786.

Kaarstad, O., and H. Audus, 1997: Hydrogen and electricity from decarbonised fossil fuels. Energy Convers. Mgmt., 38 (Suppl.), S431-S442.

Kartha, S., and P. Grimes, 1994: Fuel cells: energy conversion for the next century. Physics Today, 47 (11), 54-61, November.

Ogden, J., M. Steinbugler, and T. Kreutz, 1997: Hydrogen as a fuel for fuel cell vehicles: a technical and economic comparison. Proceedings of the 8th Annual Hydrogen Meeting: Hydrogen Partnerships for the Future (Arlington, VA, 11-13 March), National Hydrogen Association, Washington, DC, 469-506.

Office of Fossil Energy (U.S. Department of Energy), 1997: Coal and Power Systems R&D Program, July.

Parsons I&GT (Parsons Infrastructure and Technology Group, Inc., Reading, PA), 1998: Decarbonized fuel plants utilizing inorganic membranes for hydrogen production. Paper presented at the 12th Annual Conference on Fossil Fuels Materials, Knoxville, TN, 12-14 May

PCAST Energy R&D Panel, 1997. Federal Energy Research and Development for the Challenges of the Twenty-First Century. Report of the Energy Research and Development Panel of the

President's Committee of Advisors on Science and Technology (PCAST), November. Available on the World Wide Web at HYPERLINK http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html

http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html

Penner, S.S., A.J. Appleby, B.S. Baker, J.L. Bates, L.B. Buss, W.J. Dollard, P.J. Farris, E.A. Gillis, J.A. Gunsher, A. Khandkar, M. Krumpelt, J.B. O'Sullivan, G. Runte, R.F. Savinell, J.R. Selman, D.A. Shores, and P. Tarman, 1995: Commercialization of fuel cells. Energy The International Journal, 20 (5), 331-470.

Reddy, A.K.N, R.H. Williams, and T.B. Johansson, 1997: Energy After Rio: Prospects and Challenges. United Nations Development Programme, New York, 176 pp.

Ringland, J.T, 1994: Safety Issues for Hydrogen-Powered Vehicles, Sandia National Laboratories, March.

Socolow, R.H., ed., 1997: Fuels Decarbonization and Carbon Sequestration: Report of a Workshop by the Members of the Report Committee. PU/CEES Report No. 302, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, September. Available on the World Wide Web at HYPERLINK http://www.princeton.edu/~ceesdoe

http://www.princeton.edu/~ceesdoe

Spencer, D., and J. White, 1998: Innovative CO_2 separation and sequestration processes for treating multicomponent gas streams. Proceedings of the 23rd International Technical Conference on Coal Utilization & Fuel Systems. Clearwater, FLA, March 9-13, 639-663.

Steinbugler, M.,M., and R.H. Williams, 1998: The future of fuel cell vehicles. Forum for Applied Research and Public Policy, 13 (3), Fall (in the press)

Turkenburg, W.C., 1992: CO_2 removal: some conclusions. In: Proceedings of the First International Conference on Carbon Dioxide Removal. [Blok, K., W. Turkenburg, C. Hendriks, and M. Steinberg, (eds.)]. Energy Conversion and Management, 33 (5-8), 819-823.

Williams, R.H.,1998a: Fuel decarbonization for fuel cell applications and sequestration of the separated CO_2, in Eco-restructuring: Implications for Sustainable Development, Ayres (ed.), United Nations University Press, 180-222

Williams, R.H.,1998b: Fuel cells, coal, and China, in Proceedings of the 9th Annual Hydrogen Meeting,: Implementing a Global Energy Solution (Vienna, VA, 3-5 March 1998), National Hydrogen Association, Washington, DC

Williams, R.H., E. D. Larson, R. E. Katofsky, and J. Chen, 1995: Methanol and hydrogen from biomass for transportation, Energy for Sustainable Development, 1 (5), 18-34.