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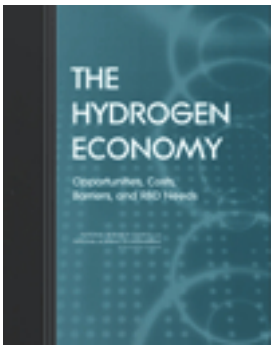

The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs

Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council, National Academy of Engineering

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The announcement of a hydrogen fuel initiative in the President's 2003 State of the Union speech substantially increased interest in the potential for hydrogen to play a major role in the nation's long-term energy future. Prior to that event, DOE asked the National Research Council to examine key technical issues about the hydrogen economy to assist in the development of its hydrogen R&D program. Included in the assessment were the current state of technology; future cost estimates; CO2 emissions; distribution, storage, and end use considerations; and the DOE RD&D program. The report provides an assessment of hydrogen as a fuel in the nation's future energy economy and describes a number of important challenges that must be overcome if it is to make a major energy contribution. Topics covered include the hydrogen end-use technologies, transportation, hydrogen production technologies, and transition issues for hydrogen in vehicles.

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Executive Summary

The National Academies' National Research Council appointed the Committee on Alternatives and Strategies for Future Hydrogen Production and Use in the fall of 2002 to address the complex subject of the "hydrogen economy." In particular, the committee carried out these tasks:

- Assessed the current state of technology for producing hydrogen from a variety of energy sources;
- Made estimates on a consistent basis of current and future projected costs, carbon dioxide (CO_2) emissions, and energy efficiencies for hydrogen technologies;
- Considered scenarios for the potential penetration of hydrogen into the economy and associated impacts on oil imports and CO_2 gas emissions;
- Addressed the problem of how hydrogen might be distributed, stored, and dispensed to end uses—together with associated infrastructure issues—with particular emphasis on light-duty vehicles in the transportation sector;
- Reviewed the U.S. Department of Energy's (DOE's) research, development, and demonstration (RD&D) plan for hydrogen; and
- Made recommendations to the DOE on RD&D, including directions, priorities, and strategies.

The vision of the hydrogen economy is based on two expectations: (1) that hydrogen can be produced from domestic energy sources in a manner that is affordable and environmentally benign, and (2) that applications using hydrogen—fuel cell vehicles, for example—can gain market share in competition with the alternatives. To the extent that these expectations can be met, the United States, and indeed the world, would benefit from reduced vulnerability to energy disruptions and improved environmental quality, especially through lower carbon emissions. However, before this vision can become a reality, many technical, social, and policy challenges must be overcome. This report focuses on the steps that should be taken to move toward the hydrogen vision and to achieve the sought-after benefits. The report focuses exclusively on hydrogen, although it notes that alternative or complementary strategies might also serve these same goals well.

The Executive Summary presents the basic conclusions of the report and the major recommendations of the committee. The report's chapters present additional findings and recommendations related to specific technologies and issues that the committee considered.

BASIC CONCLUSIONS

As described below, the committee's basic conclusions address four topics: implications for national goals, priorities for research and development (R&D), the challenge of transition, and the impacts of hydrogen-fueled light-duty vehicles on energy security and CO_2 emissions.

Implications for National Goals

A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants.[1] In his State of the Union address of January 28, 2003, President Bush moved energy, and especially hydrogen for vehicles, to the forefront of the U.S. political and technical debate. The President noted: "A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from

[1]Criteria pollutants are air pollutants (e.g., lead, sulfur dioxide, and so on) emitted from numerous or diverse stationary or mobile sources for which National Ambient Air Quality Standards have been set to protect human health and public welfare.

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laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."[2] This committee believes that investigating and conducting RD&D activities to determine whether a hydrogen economy might be realized are important to the nation. There is a potential for replacing essentially all gasoline with hydrogen over the next half century using only domestic resources. And there is a potential for eliminating almost all CO_2 and criteria pollutants from vehicular emissions. However, there are currently many barriers to be overcome before that potential can be realized.

Of course there are other strategies for reducing oil imports and CO_2 emissions, and thus the DOE should keep a balanced portfolio of R&D efforts and continue to explore supply-and-demand alternatives that do not depend upon hydrogen. If battery technology improved dramatically, for example, all-electric vehicles might become the preferred alternative. Furthermore, hybrid electric vehicle technology is commercially available today, and benefits from this technology can therefore be realized immediately. Fossil-fuel-based or biomass-based synthetic fuels could also be used in place of gasoline.

Research and Development Priorities

There are major hurdles on the path to achieving the vision of the hydrogen economy; the path will not be simple or straightforward. Many of the committee's observations generalize across the entire hydrogen economy: the hydrogen system must be cost-competitive, it must be safe and appealing to the consumer, and it would preferably offer advantages from the perspectives of energy security and CO_2 emissions. Specifically for the transportation sector, dramatic progress in the development of fuel cells, storage devices, and distribution systems is especially critical. Widespread success is not certain.

The committee believes that for hydrogen-fueled transportation, the four most fundamental technological and economic challenges are these:

1. *To develop and introduce cost-effective, durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems.* Current fuel cell lifetimes are much too short and fuel cell costs are at least an order of magnitude too high. An on-board vehicular hydrogen storage system that has an energy density approaching that of gasoline systems has not been developed. Thus, the resulting range of vehicles with existing hydrogen storage systems is much too short.

2. *To develop the infrastructure to provide hydrogen for the light-duty-vehicle user.* Hydrogen is currently produced in large quantities at reasonable costs for industrial purposes. The committee's analysis indicates that at a future, mature stage of development, hydrogen (H_2) can be produced and used in fuel cell vehicles at reasonable cost. The challenge, with today's industrial hydrogen as well as tomorrow's hydrogen, is the high cost of distributing H_2 to dispersed locations. This challenge is especially severe during the early years of a transition, when demand is even more dispersed. The costs of a mature hydrogen pipeline system would be spread over many users, as the cost of the natural gas system is today. But the transition is difficult to imagine in detail. It requires many technological innovations related to the development of small-scale production units. Also, nontechnical factors such as financing, siting, security, environmental impact, and the perceived safety of hydrogen pipelines and dispensing systems will play a significant role. All of these hurdles must be overcome before there can be widespread use. An initial stage during which hydrogen is produced at small scale near the small user seems likely. In this case, production costs for small production units must be sharply reduced, which may be possible with expanded research.

3. *To reduce sharply the costs of hydrogen production from renewable energy sources, over a time frame of decades.* Tremendous progress has been made in reducing the cost of making electricity from renewable energy sources. But making hydrogen from renewable energy through the intermediate step of making electricity, a premium energy source, requires further breakthroughs in order to be competitive. Basically, these technology pathways for hydrogen production make electricity, which is converted to hydrogen, which is later converted by a fuel cell back to electricity. These steps add costs and energy losses that are particularly significant when the hydrogen competes as a commodity transportation fuel—leading the committee to believe that most current approaches—except possibly that of wind energy—need to be redirected. The committee believes that the required cost reductions can be achieved only by targeted fundamental and exploratory research on hydrogen production by photobiological, photochemical, and thin-film solar processes.

4. *To capture and store ("sequester") the carbon dioxide by-product of hydrogen production from coal.* Coal is a massive domestic U.S. energy resource that has the potential for producing cost-competitive hydrogen. However, coal processing generates large amounts of CO_2. In order to reduce CO_2 emissions from coal processing in a carbon-constrained future, massive amounts of CO_2 would have to be captured and safely and reliably sequestered for hundreds of years. Key to the commercialization of a large-scale, coal-based hydrogen production option (and also for natural-gas-based options) is achieving broad public acceptance, along with additional technical development, for CO_2 sequestration.

For a viable hydrogen transportation system to emerge, all four of these challenges must be addressed.

[2] *Weekly Compilation of Presidential Documents.* Monday, February 3, 2003. Vol. 39, No. 5, p. 111. Washington, D.C.: Government Printing Office.

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The Challenge of Transition

There will likely be a lengthy transition period during which fuel cell vehicles and hydrogen are not competitive with internal combustion engine vehicles, including conventional gasoline and diesel fuel vehicles, and hybrid gasoline electric vehicles. The committee believes that the transition to a hydrogen fuel system will best be accomplished initially through distributed production of hydrogen, because distributed generation avoids many of the substantial infrastructure barriers faced by centralized generation. Small hydrogen-production units located at dispensing stations can produce hydrogen through natural gas reforming or electrolysis. Natural gas pipelines and electricity transmission and distribution systems already exist; for distributed generation of hydrogen, these systems would need to be expanded only moderately in the early years of the transition. During this transition period, distributed renewable energy (e.g., wind or solar energy) might provide electricity to onsite hydrogen production systems, particularly in areas of the country where electricity costs from wind or solar energy are particularly low. A transition emphasizing distributed production allows time for the development of new technologies and concepts capable of potentially overcoming the challenges facing the widespread use of hydrogen. The distributed transition approach allows time for the market to develop before too much fixed investment is set in place. While this approach allows time for the ultimate hydrogen infrastructure to emerge, the committee believes that it cannot yet be fully identified and defined.

Impacts of Hydrogen-Fueled Light-Duty Vehicles

Several findings from the committee's analysis (see Chapter 6) show the impact on the U.S. energy system if successful market penetration of hydrogen fuel cell vehicles is achieved. In order to analyze these impacts, the committee posited that fuel cell vehicle technology would be developed successfully and that hydrogen would be available to fuel light-duty vehicles (cars and light trucks). These findings are as follows:

- The committee's upper-bound market penetration case for fuel cell vehicles, premised on hybrid vehicle experience, assumes that fuel cell vehicles enter the U.S. light-duty vehicle market in 2015 in competition with conventional and hybrid electric vehicles, reaching 25 percent of light-duty vehicle sales around 2027. The demand for hydrogen in about 2027 would be about equal to the current production of 9 million short tons (tons) per year, which would be only a small fraction of the 110 million tons required for full replacement of gasoline light-duty vehicles with hydrogen vehicles, posited to take place in 2050.
- If coal, renewable energy, or nuclear energy is used to produce hydrogen, a transition to a light-duty fleet of vehicles fueled entirely by hydrogen would reduce total energy imports by the amount of oil consumption displaced. However, if natural gas is used to produce hydrogen, and if, on the margin, natural gas is imported, there would be little if any reduction in total energy imports, because natural gas for hydrogen would displace petroleum for gasoline.
- CO_2 emissions from vehicles can be cut significantly if the hydrogen is produced entirely from renewables or nuclear energy, or from fossil fuels with sequestration of CO_2. The use of a combination of natural gas without sequestration and renewable energy can also significantly reduce CO_2 emissions. However, emissions of CO_2 associated with light-duty vehicles contribute only a portion of projected CO_2 emissions; thus, sharply reducing overall CO_2 releases will require carbon reductions in other parts of the economy, particularly in electricity production.
- Overall, although a transition to hydrogen could greatly transform the U.S. energy system in the long run, the impacts on oil imports and CO_2 emissions are likely to be minor during the next 25 years. However, thereafter, if R&D is successful and large investments are made in hydrogen and fuel cells, the impact on the U.S. energy system could be great.

MAJOR RECOMMENDATIONS

Systems Analysis of U.S. Energy Options

The U.S. energy system will change in many ways over the next 50 years. Some of the drivers for such change are already recognized, including at present the geology and geopolitics of fossil fuels and, perhaps eventually, the rising CO_2 concentration in the atmosphere. Other drivers will emerge from options made available by new technologies. The U.S. energy system can be expected to continue to have substantial diversity; one should expect the emergence of neither a single primary energy source nor a single energy carrier. Moreover, more-energy-efficient technologies for the household, office, factory, and vehicle will continue to be developed and introduced into the energy system. The role of the DOE hydrogen program[3] in the restructuring of the overall national energy system will evolve with time.

To help shape the DOE hydrogen program, the committee sees a critical role for systems analysis. Systems analysis will be needed both to coordinate the multiple parallel efforts within the hydrogen program and to integrate the program within a balanced, overall DOE national energy R&D effort. Internal coordination must address the many primary sources from which hydrogen can be produced, the various

[3]The words "hydrogen program" refer collectively to the programs concerned with hydrogen production, distribution, and use within DOE's Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy, Office of Science, and Office of Nuclear Energy, Science, and Technology. There is no single program with this title.

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scales of production, the options for hydrogen distribution, the crosscutting challenges of storage and safety, and the hydrogen-using devices. Integration within the overall DOE effort must address the place of hydrogen relative to other secondary energy sources—helping, in particular, to clarify the competition between electricity-based, liquid-fuel-based (e.g., cellulosic ethanol), and hydrogen-based transportation. This is particularly important as clean alternative fuel internal combustion engines, fuel cells, and batteries evolve. Integration within the overall DOE effort must also address interactions with end-use energy efficiency, as represented, for example, by high-fuel-economy options such as hybrid vehicles. Implications of safety, security, and environmental concerns will need to be better understood. So will issues of timing and sequencing: depending on the details of system design, a hydrogen transportation system initially based on distributed hydrogen production, for example, might or might not easily evolve into a centralized system as density of use increases.

Recommendation ES-1. The Department of Energy should continue to develop its hydrogen initiative as a potential long-term contributor to improving U.S. energy security and environmental protection. The program plan should be reviewed and updated regularly to reflect progress, potential synergisms within the program, and interactions with other energy programs and partnerships (e.g., the California Fuel Cell Partnership). In order to achieve this objective, the committee recommends that the DOE develop and employ a systems analysis approach to understanding full costs, defining options, evaluating research results, and helping balance its hydrogen program for the short, medium, and long term. Such an approach should be implemented for all U.S. energy options, not only for hydrogen.

As part of its systems analysis, the DOE should map out and evaluate a transition plan consistent with developing the infrastructure and hydrogen resources necessary to support the committee's hydrogen vehicle penetration scenario or another similar demand scenario. The DOE should estimate what levels of investment over time are required—and in which program and project areas—in order to achieve a significant reduction in carbon dioxide emissions from passenger vehicles by midcentury.

Fuel Cell Vehicle Technology

The committee observes that the federal government has been active in fuel cell research for roughly 40 years, while proton exchange membrane (PEM) fuel cells applied to hydrogen vehicle systems are a relatively recent development (as of the late 1980s). In spite of substantial R&D spending by the DOE and industry, costs are still a factor of 10 to 20 times too expensive, these fuel cells are short of required durability, and their energy efficiency is still too low for light-duty-vehicle applications. Accordingly, the challenges of developing PEM fuel cells for automotive applications are large, and the solutions to overcoming these challenges are uncertain.

The committee estimates that the fuel cell system, including on-board storage of hydrogen, will have to decrease in cost to less than $100 per kilowatt (kW)[4] before fuel cell vehicles (FCVs) become a plausible commercial option, and that it will take at least a decade for this to happen. In particular, if the cost of the fuel cell system for light-duty vehicles does not eventually decrease to the $50/kW range, fuel cells will not propel the hydrogen economy without some regulatory mandate or incentive.

Automakers have demonstrated FCVs in which hydrogen is stored on board in different ways, primarily as high-pressure compressed gas or as a cryogenic liquid. At the current state of development, both of these options have serious shortcomings that are likely to preclude their long-term commercial viability. New solutions are needed in order to lead to vehicles that have at least a 300 mile driving range; that are compact, lightweight, and inexpensive; and that meet future safety standards.

Given the current state of knowledge with respect to fuel cell durability, on-board storage systems, and existing component costs, the committee believes that the near-term DOE milestones for FCVs are unrealistically aggressive.

Recommendation ES-2. Given that large improvements are still needed in fuel cell technology and given that industry is investing considerable funding in technology development, increased government funding on research and development should be dedicated to the research on breakthroughs in on-board storage systems, in fuel cell costs, and in materials for durability in order to attack known inhibitors of the high-volume production of fuel cell vehicles.

Infrastructure

A nationwide, high-quality, safe, and efficient hydrogen infrastructure will be required in order for hydrogen to be used widely in the consumer sector. While it will be many years before hydrogen use is significant enough to justify an integrated national infrastructure—as much as two decades in the scenario posited by the committee—regional infrastructures could evolve sooner. The relationship between hydrogen production, delivery, and dispensing is very complex, even for regional infrastructures, as it depends on many variables associated with logistics systems and on many public and private entities. Codes and standards for infrastructure development could be a significant deterrent to hydrogen advancement if not established well ahead of the hydrogen market. Similarly, since resilience to terrorist at-

[4]The cost includes the fuel cell module, precious metals, the fuel processor, compressed hydrogen storage, balance of plant, and assembly, labor, and depreciation.

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tack has become a major performance criterion for any infrastructure system, the design of future hydrogen infrastructure systems may need to consider protection against such risks.

In the area of infrastructure and delivery there seem to be significant opportunities for making major improvements. The DOE does not yet have a strong program on hydrogen infrastructures. DOE leadership is critical, because the current incentives for companies to make early investments in hydrogen infrastructure are relatively weak.

Recommendation ES-3a. The Department of Energy program in infrastructure requires greater emphasis and support. The Department of Energy should strive to create better linkages between its seemingly disconnected programs in large-scale and small-scale hydrogen production. The hydrogen infrastructure program should address issues such as storage requirements, hydrogen purity, pipeline materials, compressors, leak detection, and permitting, with the objective of clarifying the conditions under which large-scale and small-scale hydrogen production will become competitive, complementary, or independent. The logistics of interconnecting hydrogen production and end use are daunting, and all current methods of hydrogen delivery have poor energy-efficiency characteristics and difficult logistics. Accordingly, the committee believes that exploratory research focused on new concepts for hydrogen delivery requires additional funding. The committee recognizes that there is little understanding of future logistics systems and new concepts for hydrogen delivery—thus making a systems approach very important.

Recommendation ES-3b. The Department of Energy should accelerate work on codes and standards and on permitting, addressing head-on the difficulties of working across existing and emerging hydrogen standards in cities, counties, states, and the nation.

Transition

The transition to a hydrogen economy involves challenges that cannot be overcome by research and development and demonstrations alone. Unresolved issues of policy development, infrastructure development, and safety will slow the penetration of hydrogen into the market even if the technical hurdles of production cost and energy efficiency are overcome. Significant industry investments in advance of market forces will not be made unless government creates a business environment that reflects societal priorities with respect to greenhouse gas emissions and oil imports.

Recommendation ES-4. The policy analysis capability of the Department of Energy with respect to the hydrogen economy should be strengthened, and the role of government in supporting and facilitating industry investments to help bring about a transition to a hydrogen economy needs to be better understood.

The committee believes that a hydrogen economy will not result from a straightforward replacement of the present fossil-fuel-based economy. There are great uncertainties surrounding a transition period, because many innovations and technological breakthroughs will be required to address the costs and energy-efficiency, distribution, and nontechnical issues. The hydrogen fuel for the very early transitional period, before distributed generation takes hold, would probably be supplied in the form of pressurized or liquefied molecular hydrogen, trucked from existing, centralized production facilities. But, as volume grows, such an approach may be judged too expensive and/or too hazardous. It seems likely that, in the next 10 to 30 years, hydrogen produced in distributed rather than centralized facilities will dominate. Distributed production of hydrogen seems most likely to be done with small-scale natural gas reformers or by electrolysis of water; however, new concepts in distributed production could be developed over this time period.

Recommendation ES-5. Distributed hydrogen production systems deserve increased research and development investments by the Department of Energy. Increased R&D efforts and accelerated program timing could decrease the cost and increase the energy efficiency of small-scale natural gas reformers and water electrolysis systems. In addition, a program should be initiated to develop new concepts in distributed hydrogen production systems that have the potential to compete—in cost, energy efficiency, and safety—with centralized systems. As this program develops new concepts bearing on the safety of local hydrogen storage and delivery systems, it may be possible to apply these concepts in large-scale hydrogen generation systems as well.

Safety

Safety will be a major issue from the standpoint of commercialization of hydrogen-powered vehicles. Much evidence suggests that hydrogen can be manufactured and used in professionally managed systems with acceptable safety, but experts differ markedly in their views of the safety of hydrogen in a consumer-centered transportation system. A particularly salient and underexplored issue is that of leakage in enclosed structures, such as garages in homes and commercial establishments. Hydrogen safety, from both a technological and a societal perspective, will be one of the major hurdles that must be overcome in order to achieve the hydrogen economy.

Recommendation ES-6. The committee believes that the Department of Energy program in safety is well planned and should be a priority. However, the committee emphasizes the following:

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- Safety policy goals should be proposed and discussed by the Department of Energy with stakeholder groups early in the hydrogen technology development process.
- The Department of Energy should continue its work with standards development organizations and ensure increased emphasis on distributed production of hydrogen.
- Department of Energy systems analysis should specifically include safety, and it should be understood to be an overriding criterion.
- The goal of the physical testing program should be to resolve safety issues in advance of commercial use.
- The Department of Energy's public education program should continue to focus on hydrogen safety, particularly the safe use of hydrogen in distributed production and in consumer environments.

Carbon Dioxide-Free Hydrogen

The long timescale associated with the development of viable hydrogen fuel cells and hydrogen storage provides a time window for a more intensive DOE program to develop hydrogen from electrolysis, which, if economic, has the potential to lead to major reductions in CO_2 emissions and enhanced energy security. The committee believes that if the cost of fuel cells can be reduced to $50 per kilowatt, with focused research a corresponding dramatic drop in the cost of electrolytic cells to electrolyze water can be expected (to ~$125/kW). If such a low electrolyzer cost is achieved, the cost of hydrogen produced by electrolysis will be dominated by the cost of the electricity, not by the cost of the electrolyzer. Thus, in conjunction with research to lower the cost of electrolyzers, research focused on reducing electricity costs from renewable energy and nuclear energy has the potential to reduce overall hydrogen production costs substantially.

Recommendation ES-7. The Department of Energy should increase emphasis on electrolyzer development, with a target of $125 per kilowatt and a significant increase in efficiency toward a goal of over 70 percent (lower heating value basis). In such a program, care must be taken to properly account for the inherent intermittency of wind and solar energy, which can be a major limitation to their wide-scale use. In parallel, more aggressive electricity cost targets should be set for unsubsidized nuclear and renewable energy that might be used directly to generate electricity. Success in these areas would greatly increase the potential for carbon dioxide-free hydrogen production.

Carbon Capture and Storage

The DOE's various efforts with respect to hydrogen and fuel cell technology will benefit from close integration with carbon capture and storage (sequestration) activities and programs in the Office of Fossil Energy. If there is an expanded role for hydrogen produced from fossil fuels in providing energy services, the probability of achieving substantial reductions in net CO_2 emissions through sequestration will be greatly enhanced through close program integration. Integration will enable the DOE to identify critical technologies and research areas that can enable hydrogen production from fossil fuels with CO_2 capture and storage. Close integration will promote the analysis of overlapping issues such as the co-capture and co-storage with CO_2 of pollutants such as sulfur produced during hydrogen production.

Many early carbon capture and storage projects will not involve hydrogen, but rather will involve the capture of the CO_2 impurity in natural gas, the capture of CO_2 produced at electric plants, or the capture of CO_2 at ammonia and synfuels plants. All of these routes to capture, however, share carbon storage as a common component, and carbon storage is the area in which the most difficult institutional issues and the challenges related to public acceptance arise.

Recommendation ES-8. The Department of Energy should tighten the coupling of its efforts on hydrogen and fuel cell technology with the DOE Office of Fossil Energy's programs on carbon capture and storage (sequestration). Because of the hydrogen program's large stake in the successful launching of carbon capture and storage activity, the hydrogen program should participate in all of the early carbon capture and storage projects, even those that do not directly involve carbon capture during hydrogen production. These projects will address the most difficult institutional issues and the challenges related to issues of public acceptance, which have the potential of delaying the introduction of hydrogen in the marketplace.

The Department of Energy's Hydrogen Research, Development, and Demonstration Plan

As part of its effort, the committee reviewed the DOE's draft "Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan," dated June 3, 2003 (DOE, 2003b). The committee's deliberations focused only on the hydrogen production and demand portion of the overall DOE plan. For example, while the committee makes recommendations on the use of renewable energy for hydrogen production, it did not review the entire DOE renewables program in depth. The committee is impressed by how well the hydrogen program has progressed. From its analysis, the committee makes two overall observations about the program:

- First, the plan is focused primarily on the activities in the Office of Hydrogen, Fuel Cells, and Infrastructure Technologies Program within the Office of Energy Efficiency and Renewable Energy, and on some activities in the Office of Fossil Energy. The activities related to hydrogen in the Office of Nuclear Energy, Science, and Technology, and in the Office of Science, as well as activities related to carbon cap-

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ture and storage in the Office of Fossil Energy, are important, but they are mentioned only casually in the plan. The development of an overall DOE program will require better integration across all DOE programs.

- Second, the plan's priorities are unclear, as they are lost within the myriad of activities that are proposed. The general budget for DOE's hydrogen program is contained in the appendix of the plan, but the plan provides no dollar numbers at the project level, even for existing projects and programs. The committee found it difficult to judge the priorities and the go/no-go decision points for each of the R&D areas.

Recommendation ES-9. The Department of Energy should continue to develop its hydrogen research, development, and demonstration (RD&D) plan to improve the integration and balance of activities within the Office of Energy Efficiency and Renewable Energy; the Office of Fossil Energy (including programs related to carbon sequestration); the Office of Nuclear Energy, Science, and Technology; and the Office of Science. The committee believes that, overall, the production, distribution, and dispensing portion of the program is probably underfunded, particularly because a significant fraction of appropriated funds is already earmarked. The committee understands that of the $78 million appropriated for hydrogen technology for FY 2004 in the Energy and Water appropriations bill (Public Law 108-137), $37 million is earmarked for activities that will not particularly advance the hydrogen initiative. The committee also believes that the hydrogen program, in an attempt to meet the extreme challenges set by senior government and DOE leaders, has tried to establish RD&D activities in too many areas, creating a very diverse, somewhat unfocused program. Thus, prioritizing the efforts both within and across program areas, establishing milestones and go/no-go decisions, and adjusting the program on the basis of results are all extremely important in a program with so many challenges. This approach will also help determine when it is appropriate to take a program to the demonstration stage. And finally, the committee believes that the probability of success in bringing the United States to a hydrogen economy will be greatly increased by partnering with a broader range of academic and industrial organizations—possibly including an international focus[5]—and by establishing an independent program review process and board.

Recommendation ES-10. There should be a shift in the hydrogen program away from some development areas and toward exploratory work—as has been done in the area of hydrogen storage. A hydrogen economy will require a number of technological and conceptual breakthroughs. The Department of Energy program calls for increased funding in some important exploratory research areas such as hydrogen storage and photoelectrochemical hydrogen production. However, the committee believes that much more exploratory research is needed. Other areas likely to benefit from an increased emphasis on exploratory research include delivery systems, pipeline materials, electrolysis, and materials science for many applications. The execution of such changes in emphasis would be facilitated by the establishment of DOE-sponsored academic energy research centers. These centers should focus on interdisciplinary areas of new science and engineering—such as materials research into nanostructures, and modeling for materials design—in which there are opportunities for breakthrough solutions to energy issues.

Recommendation ES-11. As a framework for recommending and prioritizing the Department of Energy program, the committee considered the following:

- Technologies that could significantly impact U.S. energy security and carbon dioxide emissions,
- The timescale for the evolution of the hydrogen economy,
- Technology developments needed for both the transition period and the steady state,
- Externalities that would decelerate technology implementation, and
- The comparative advantage of the DOE in research and development of technologies at the pre-competitive stage.

The committee recommends that the following areas receive increased emphasis:

- *Fuel cell vehicle development.* Increase research and development (R&D) to facilitate breakthroughs in fuel cell costs and in durability of fuel cell materials, as well as breakthroughs in on-board hydrogen storage systems;
- *Distributed hydrogen generation.* Increase R&D in small-scale natural gas reforming, electrolysis, and new concepts for distributed hydrogen production systems;
- *Infrastructure analysis.* Accelerate and increase efforts in systems modeling and analysis for hydrogen delivery, with the objective of developing options and helping guide R&D in large-scale infrastructure development;
- *Carbon sequestration and FutureGen.* Accelerate development and early evaluation of the viability of carbon capture and storage (sequestration) on a large scale because of its implications for the long-term use of coal for hydrogen production. Continue the FutureGen Project as a high-priority task; and
- *Carbon dioxide-free energy technologies.* Increase emphasis on the development of wind-energy-to-hydrogen as an important technology for the hydrogen transition period and potentially for the longer term. Increase exploratory and fundamental research on hydrogen production by photobiological, photoelectrochemical, thin-film solar, and nuclear heat processes.

[5]Secretary of Energy Spencer Abraham, joined by ministers representing 14 nations and the European Commission, signed an agreement on November 20, 2003, to formally establish the International Partnership for the Hydrogen Economy.

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THE HYDROGEN ECONOMY

Opportunities, Costs, Barriers, and R&D Needs

Committee on Alternatives and Strategies
for Future Hydrogen Production and Use

Board on Energy and Environmental Systems

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL *AND*
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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confi-

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