COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

HEARING CHARTER

Reviewing the Hydrogen Fuel and FreedomCAR Initiatives

Wednesday, March 3, 2004
2:00 – 4:00 p.m.
2318 Rayburn House Office Building

1. Purpose

On Wednesday, March 3, 2004, the U.S. House of Representatives' Committee on Science will hold a hearing to examine the Department of Energy's (DOE) Hydrogen Fuel and FreedomCAR initiatives. Specifically, the hearing will focus on two recent reports from the National Academy of Sciences (NAS) and the American Physical Society (APS) on DOE's hydrogen initiatives, and the Administration's response to the recommendations from the reports. The hydrogen program is one of the President's primary energy initiatives, and the two reports recommend changes to the program.

2. Witnesses **WEBCAST: http://boss.streamos.com/real/hscience/sci04/mar0304.smi**

- **Mr. David Garman** is the Assistant Secretary of Energy Efficiency and Renewable Energy at the Department of Energy. Prior to joining the Department, Mr. Garman served as Chief of Staff to Alaska Senator Frank Murkowski and has served on the professional staff of the Senate Energy and Natural Resources Committee and the Senate Select Committee on Intelligence.
- **Dr. Michael Ramage** is the Chair of the National Academy of Sciences' (NAS), Committee on Alternatives and Strategies for Future Hydrogen Production and Use. Dr. Ramage is a retired executive vice president at ExxonMobil Research and Engineering Company.
- **Dr. Peter Eisenberger** is the Chair of the American Physical Society's (APS) Panel on Public Affairs Energy Subcommittee. Dr. Eisenberger is currently a Professor of Earth and Environmental Sciences at Columbia University, and has extensive academic and corporate research experience at Harvard, Stanford, Princeton, Exxon, and Bell Laboratories.

3. Overarching Questions

The hearing will address the following overarching questions:

- Are the Hydrogen Fuel and FreedomCAR initiatives on track to provide a viable alternative to petroleum as a transportation fuel?
- Are the goals of the Hydrogen Fuel and FreedomCAR initiatives appropriate and realistic? Are the initiatives designed to meet their goals?

- What are the most important recommendations from the NAS and APS reports? How is the Department responding to the recommendations?
- Will technology research alone lead to a transition to hydrogen, or will it be necessary to apply policy tools? How should a research and development effort take these policy choices into account?

4. Overview

- In his 2003 State of the Union speech, President Bush announced the creation of a new Hydrogen Fuel Initiative, which built on the FreedomCAR initiative announced in 2002. Together, the initiatives aim to provide the technology for a hydrogen-based transportation economy, including production of hydrogen, transportation and distribution of hydrogen, and the vehicles that will use the hydrogen. Fuel cell cars running on hydrogen would emit only water vapor and, if domestic energy sources were used, would not be dependent on foreign fuels.
- The recent reports from the American Physical Society (APS) and the National Academy of Sciences (NAS) both recommend changes to the hydrogen initiatives, particularly arguing for a greater emphasis on basic, exploratory research because of the significant, perhaps insurmountable, technical barriers that must be overcome. The APS report strongly cautions DOE against premature demonstration projects, saying such projects could repeat the government's unhappy experience with the synthetic fuels programs of the 1970s.
- The NAS study describes DOE's near-term milestones for fuel cell vehicles as "unrealistically aggressive." Both reports note that it will require technical breakthroughs – not just incremental improvements – to meet the goals of the overall hydrogen initiative. For example, the APS study states, "No material exists today that can be used to construct a hydrogen fuel tank that can meet the consumer benchmarks."
- The NAS study finds that in the DOE hydrogen program plan, the "priorities are unclear." The NAS study calls for "increased emphasis" on fuel cell vehicle development, distributed hydrogen generation, infrastructure analysis, carbon sequestration and carbon dioxide-free energy technologies.
- The NAS report notes that DOE needs to think about policy questions as it develops its research and development (R&D) agenda: "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…. 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 mid-century."
- While the President's fiscal year 2005 (FY05) budget request includes additional funding for hydrogen R&D, it provides the money for hydrogen research by making cuts in other energy efficiency and renewable energy R&D programs. The APS report specifically argues against such an approach, and the NAS report notes that research on other aspects of renewable energy may be necessary for a successful transition to a hydrogen economy.

- The APS report recommends that DOE continue research into bridge technologies – such as gasoline or diesel hybrids and hydrogen-fueled internal combustion engines – that could provide benefits if the commercialization of fuel cell vehicles is delayed.

5. Background

Report Recommendations

NAS report recommendations summary

The NAS report raises "four pivotal questions" about the transition to a hydrogen economy:

- When will vehicular fuel cells achieve the durability, efficiency, cost, and performance needed to gain a meaningful share of the automotive market? The future demand for hydrogen depends on the answer.
- Can carbon be captured and sequestered in a manner that provides adequate environmental protection but allows hydrogen to remain cost-competitive? The entire future of carbonaceous fuels in a hydrogen economy may depend on the answer.
- Can vehicular hydrogen storage systems be developed that offer cost and safety equivalent to that of fuels in use today? The future of transportation use depends on the answer.
- Can an economic transition to an entirely new energy infrastructure, both the supply and the demand side, be achieved in the face of competition from the accustomed benefits of the current infrastructure? The future of the hydrogen economy depends on the answer.[1]

The report examines possible answers to the questions and recommends changes to the DOE hydrogen R&D program. The study concludes that, even under the most optimistic scenario, "[T]he impacts on oil imports and CO2 emissions are likely to be minor during the next 25 years." The report goes on to add, "[T]hereafter, 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."

The report's recommendations are summarized below.

Major NAS Recommendations:

- *Systems Analysis* – DOE should undertake more systems analysis to better understand the challenges, progress, and potential benefits of making the transition to a hydrogen economy.

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[1] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. NAS pre-publication copy page 2-13.

- *Fuel Cell Vehicle Technology* – DOE should increase funding for fundamental research and development of fuel cells focusing on on-board storage systems, fuel cell costs, and durability.
- *Infrastructure* – DOE should provide “greater emphasis and support” to research, especially exploratory research, related to the creation of a hydrogen infrastructure. DOE should “create better linkages between its seemingly disconnected programs in large-scale and small-scale hydrogen production.”
- *Infrastructure* – DOE should accelerate work on codes and standards, particularly addressing overlapping regulation at the municipal, state, and Federal levels.
- *Transition* – DOE should strengthen its policy analysis to better understand what government actions will be needed to bring about a hydrogen economy.
- *Transition* – DOE should increase investments in research and development related to distributed hydrogen production.
- *Safety* – DOE should make changes to hydrogen safety programs, including developing safety policy goals with stakeholders.
- *Carbon Dioxide-Free Hydrogen* – DOE should increase emphasis on electrolyzer development with a target of $125 per kilowatt with 70 percent efficiency. In parallel, DOE should set more aggressive electricity cost targets for unsubsidized nuclear and renewable energy that might be used to produce hydrogen.
- *Carbon Capture and Storage* – DOE should link its hydrogen programs more closely with its programs on carbon sequestration (which are managed by Fossil Energy).
- *RDD Plan* – DOE should set clearer priorities for hydrogen R&D and better integrate related programs spread among several DOE offices. Congress should stop earmarking funds for hydrogen R&D.
- *RDD Plan* – DOE should shift work away from development and toward exploratory work and should establish interdisciplinary energy research centers at universities.
- *Framework*– DOE should give greater emphasis to fuel cell vehicle development, distributed hydrogen generation, infrastructure analysis, carbon sequestration and FutureGen, and carbon dioxide-free energy technologies.

APS report recommendations summary

The APS recommendations are generally consistent with those of NAS. The primary recommendation of the APS report is that DOE should significantly increase the funding for basic research in the hydrogen initiative, while reducing the funding for demonstrations. The report outlines the various technical barriers facing each stage of hydrogen usage, and the fundamental research breakthroughs that are needed to make the initiative a success. APS concludes that large-scale demonstrations are generally premature because so many technological hurdles still must be cleared.

The APS report also recommends that the Administration increase funding for “bridge” technologies – such as hydrogen internal combustion engines and gasoline and diesel hybrid vehicles – that would provide benefits sooner than hydrogen fuel cell vehicles, particularly if technical barriers slow the market penetration of the fuel cell vehicles. The APS report also argues that the hydrogen initiatives should not displace other efficiency and renewable energy research if the goals of the initiative are to be met. Renewable energy generation, APS argues, is crucial to supplying clean, domestic energy for hydrogen production.

Challenges

What are the technical challenges?

Major advances are needed across a wide range of technologies if hydrogen is to be affordable, safe, cleanly produced, and readily distributed. The production, storage and use of hydrogen all present significant challenges.

Hydrogen can be produced from a variety of sources, including coal and natural gas. But one goal of using hydrogen is to reduce emissions of carbon dioxide. If hydrogen is to be produced without emissions of carbon dioxide, then the technology to capture and store carbon dioxide (known as carbon sequestration) must improve significantly. The other main goal of using hydrogen is to reduce the use of imported energy. Today most hydrogen is produced from natural gas, but in order to supply the entire transportation sector significant imports of natural gas would be required. Other possible means of producing hydrogen are inherently cleaner than coal, but are far from affordable with existing technology. For example, the APS estimates that hydrogen produced through electrolysis is currently four to ten times more expensive than gasoline.

Another major hurdle is finding ways to store hydrogen, particularly on board a vehicle. APS believes "a new material must be discovered" to develop an affordable hydrogen fuel tank.

The NAS estimates that fuel cells themselves will need a ten- to twenty-fold improvement before fuel cell vehicles become competitive with conventional technology. Today's fuel cells also wear out quickly, and are therefore far short of the durability that would be required to compete with a gasoline engine. Finally, if hydrogen is going to be produced on a large-scale, dramatic improvements in pipeline and tanker technology are required to permit the efficient and safe transportation and distribution of hydrogen. Small-scale distributed production also needs improvement, and the NAS report recommends increased focus in that area because it may be the first to develop.

What are the non-technical challenges? (policy, regulatory, inertia, public awareness)

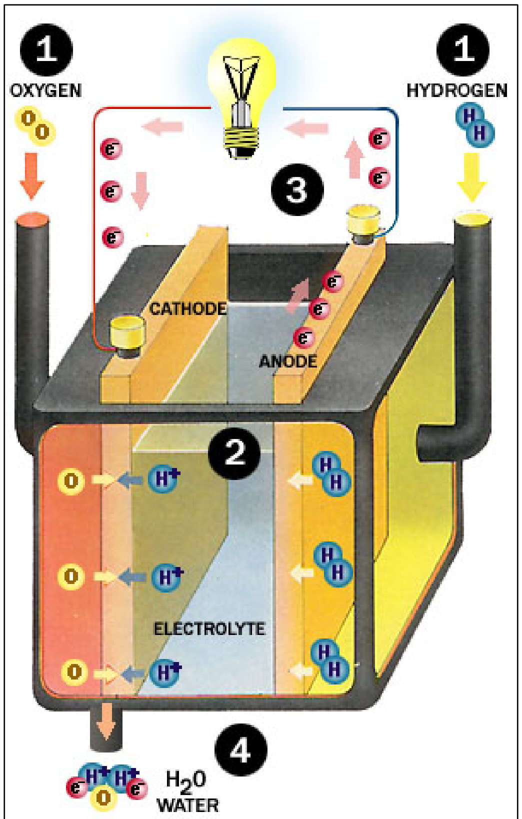
Even if the technology advances to a point at which it is competitive, the transition to a hydrogen economy will require an enormous investment to create a new infrastructure. Changes in regulation, training and public habits and attitudes will also be necessary. Estimates of the cost of creating a fueling infrastructure (replacing or altering gas stations) alone are in the hundreds of billions of dollars.

The transition also won't happen quickly. According to the NAS study, significant sales of hydrogen vehicles are unlikely before 2025 even under the most optimistic technology assumptions.

Technology

What is a Fuel Cell?

Central to the operation of the hydrogen-based economy is a device known as a fuel cell that would convert hydrogen fuels to electricity. In cars, these devices would be connected to electric motors that would provide the power now supplied by gasoline engines. A fuel cell produces electricity by means of an electrochemical reaction much like a battery. However, there is an important difference. Rather than using up the chemicals inside the cells, a fuel cell uses hydrogen fuel, and oxygen extracted from the air, to produce electricity. As long as hydrogen fuel and oxygen are fed into the fuel cell, it will continue to generate electric power.



1. Hydrogen gas is extracted from natural gas or other sources and permeates the anode. Oxygen from the air permeates the cathode.
2. Aided by a catalyst in the anode, electrons are stripped from the hydrogen. Hydrogen ions pass into the electrolyte.
3. Electrons cannot enter the electrolyte. They travel through an external circuit, producing electricity.
4. Electrons travel back to the cathode where they combine with hydrogen ions and oxygen to form water.

Source - DOE

Different types of fuel cells work with different electrochemical reactions. Currently most automakers are considering Proton Exchange Membrane (PEM) fuel cells for their vehicles.

Benefits of a Hydrogen-based Economy

A hydrogen-based economy could have two important benefits. First, hydrogen can be manufactured from a variety of sources, including natural gas, biofuels, petroleum, coal, and even by passing electricity through water (electrolysis). Depending on the choice of source, hydrogen could substantially reduce our dependence on foreign oil and natural gas.

Second, the consumption of hydrogen through fuel cells yields water as its only emission. Other considerations, such as the by-products of the hydrogen production process, will also be important in choosing the source of the hydrogen. For example, natural gas is the current feedstock for industrial hydrogen, but its production releases carbon dioxide; production from coal releases more carbon dioxide and other emissions; and production from water means that pollution may be created by the generation of electricity used in electrolysis. Production from solar electricity would mean no pollution in the generation process or in consumption, but is currently more expensive and less efficient than other methods.

Table 1. Current Federal Activities

Hydrogen Initiatives Budget ($ million)					
Department/Office	**2003 Actual***	**2004 Enacted****	**2005 Request**	**Dollar Change, 2004 to 2005**	**Percent Change, 2004 to 2005**
Energy / EERE Hydrogen Fuel	92	147	173	26	17
Energy / EERE FreedomCAR	152	155	169	14	9
Energy / Fossil Energy (coal)	2	5	16	11	227
Energy / Nuclear Energy	2	6	9	3	41
Energy / Basic Energy Sciences	0***	0***	29	29	-
Department of Transportation	0	0.6	0.8	0.3	50
TOTAL ******	**180**	**249**	**319**	**71**	**28**

* Reflects funding for baseline activities that the Hydrogen Fuel Initiative (HFI) augments and/or redirects. 2004 was the first year for the HFI, 2003 was the first year for FreedomCAR.
** Reflects rescissions, general reductions, and other adjustments included in relevant 2004 appropriations.
*** Base funding for hydrogen-related activities in Basic Energy Sciences was roughly $8 million in 2003 and 2004. These activities have been reoriented and expanded to support the goals of the President's HFI in 2005.
**** Columns do not add due to FreedomCAR and HFI funding overlaps and rounding.

Industry participation

Although exact numbers on industry involvement are proprietary, the major automobile companies have invested billions of dollars in R&D and demonstrations of fuel cell vehicles. General Motors alone had spent $1 billion as of June 2003, and estimated that its total investment by 2010 could triple.

Legislation

Language in the portion of the comprehensive Energy Bill (H.R. 6) produced by the Science Committee would authorize and guide the hydrogen initiative. The conference report on H.R. 6 is still pending in the Senate.

6. Questions to the Witnesses

The witnesses have been asked to address the National Academy of Sciences' (NAS) and American Physical Society's (APS) recent reports and recommendations on the hydrogen initiatives in their testimony, and in addition the following specific questions.

Mr. David Garman:

1. The NAS report describes the goals of the initiatives as "unrealistically aggressive" while the APS report highlights the significant "performance gaps" between current technology and the initiative milestones. Does the Department of Energy (DOE) plan to adjust the goals based on the comments of these reports? If not, how does DOE plan to respond?

2. Because of the significant technical challenges, both reports criticized the current mix of funding for hydrogen research, arguing that more emphasis should be placed on fundamental research as opposed to demonstrations. Please describe the hydrogen program's current demonstration and deployment efforts, and how each technology element's current costs and performance measure against the program goals. Does DOE plan to adjust the balance of funding to match the recommendations? If not, why?

3. The NAS report suggests that the research agenda should be developed with future policy decisions in mind. How did the Administration consider the impact of future policy decisions in the development of the research agenda for the hydrogen initiatives? Does DOE plan on increasing its policy analysis capabilities as recommended by the NAS?

4. What are the key criteria for deciding that a technology is ready for demonstration? Are there guidelines or rules of thumb, such as 120 percent of cost goals, or 85 percent of performance goals that indicate that a technology is ready for demonstration-scale activities?

5. Using the definitions in OMB Circular A-11, what is the proposed mix of funding in the FY05 budget request between basic research, applied research, development, demonstration, and deployment activities within the Hydrogen Fuel Initiative?

Dr. Michael Ramage:

1. Given the current state of hydrogen technology, what do you feel the federal funding balance should be between demonstration and research?

2. One of the recommendations included in the NAS report calls for an expanded policy analysis program at the Department of Energy. Please describe why the committee felt this was important, and give more detail as to what such a program might encompass.

3. In the penetration models included in the NAS study, the committee assumes that the technical goals will be met, even though they are deemed overly optimistic. What would be more realistic goals? How would that affect the penetration models? What would that imply for the delivery of public benefits such as environmental improvements and reduced oil dependence?

4. What are the key criteria for deciding that a technology is ready for demonstration? Are there guidelines or rules of thumb, such as reaching 120 percent of cost goals, or 85 percent of performance goals, that indicate that a technology is ready for demonstration-scale activities?

5. While the NAS report recommends shifting funding away from "bridge" technologies such as gasoline and diesel hybrids and hydrogen internal combustion engines, another recently released report from the American Physical Society (APS) encourages DOE to increase funding in these areas in light of their near term benefits. How would you respond to the APS recommendation? What do you feel is the reason for the different opinions about Federal investment in bridge technologies?

Dr. Peter Eisenberger:

1. One of the major themes of the APS report is the lack of funding for basic research. The report notes that the Department's request of $29 million in the Office of Science for fiscal year 2005 was a dramatic improvement, but says that the amount of basic research is still inadequate at 13 percent of the overall hydrogen funding. What do you feel the balance should be? How should it change over time?

2. What are the key criteria for deciding that a technology is ready for demonstration? Are there guidelines or rules of thumb, such as reaching 120 percent of cost goals, or 85 percent of performance goals, that indicate that a technology is ready for demonstration-scale activities?

3. While the APS report encourages DOE to increase funding to "bridge" technologies such as gasoline and diesel hybrids and hydrogen internal combustion engines, another recently released report from the National Academy of Sciences (NAS) recommends shifting funds away from bridge technologies. How would you respond to the NAS recommendation? What do you feel is the reason for the different opinions about Federal investment in bridge technologies?

Sherwood L. Boehlert
Chairman

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CONGRESSMAN SHERWOOD BOEHLERT (R-NY)
OPENING STATEMENT FOR HYDROGEN HEARING
March 3, 2004

I want to welcome everyone here for this important hearing on one of the President's key initiatives. This hearir is important because what's at stake, over the long term, is the security of our nation, the availability of resourc for economic growth here and around the world, and the health of the environment, nationally and globally. Not exactly minor issues.

The President is to be congratulated for his foresight in proposing the hydrogen initiative. It will take at least a decade of focused effort to lay the foundations for a hydrogen economy.

The question before us today is not whether to have a hydrogen initiative, but how to make sure we get the mo out of what we're spending on this program. If we think of the hydrogen initiative as a car - an appropriate analogy - then I would say that the President has bought us the car and the Secretary of Energy has turned the ignition key, but everyone is still learning how to drive, and no one has mapped out a clear travel plan yet. So, we're at a critical juncture in the development of this initiative. And I'm pleased that we'll be able to get guidance today from two prestigious organizations, the National Academy of Sciences and the American Physical Society, represented here by two distinguished researchers.

I found the recommendations in their two reports to be compelling. And I hope we'll be able to hear some specifics today about exactly how the Department of Energy (DOE) is going to implement them. Clearly this is valuable program that could be better focused, with greater emphasis on solving fundamental questions. I'm pleased that we have Secretary Garman back with us today to tell us how DOE intends to proceed. He is a leading light in the Department and a true believer in these technologies, and he has his work cut out for him with this initiative. I also want to thank Secretary Garman for appearing before us during a week in which he already has many Congressional appearances. But I'm sure that as a former Senate staffer he feels he just cai spend too much time up here.

Before we hear from our witnesses, I want to highlight two points made in these reports that go beyond the technical recommendations - points I've made in previous hearings on this subject.

First, both reports acknowledge that there is no way to discuss the transition to a hydrogen economy - or the research to get us there - without dealing forthrightly with policy questions. No mysterious market force alone is going to produce a hydrogen economy. I would urge DOE again to make that acknowledgement itself and to plan accordingly. We can't, for example, have a sensible hydrogen R&D agenda without making some decisior about how essential carbon sequestration is going to be in a hydrogen economy. Personally, I think it has to be essential, but we need a decision by DOE.

Second, both reports note that other work on energy efficiency and renewable energy is necessary for a hydrogen economy to be clean and affordable - and both reports are right. So I think it's unfortunate that the Administration proposes to pay for hydrogen research by cutting the rest of Secretary Garman's programs. We've been told in the past that such triage would not occur. It shouldn't.

Finally, let me say that I also agree with these reports when they point out that hydrogen is no panacea, especially in the short-term. Work on hydrogen should not be used as an excuse to avoid steps we need to tak now - steps like stricter CAFÉ standards, like promoting hybrid vehicles, like conducting R&D on interim solutions to our energy dependence and pollution problems.

But our focus at this hearing is on the hydrogen initiative itself. I hope we can reach some consensus today on how the research agenda can be reshaped to increase the likelihood that hydrogen can some day become the answer to our energy and environmental needs.

Mr. Gordon.

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Testimony of David Garman
Assistant Secretary for
Energy Efficiency and Renewable Energy
U.S. Department of Energy
regarding the
Hydrogen Fuel and FreedomCAR Initiatives
before the
Committee on Science
U.S. House of Representatives
March 3, 2004

Mr. Chairman, Members of the Committee, I appreciate the opportunity to testify today on the President's Hydrogen Fuel Initiative and FreedomCAR Partnership. My testimony will focus on the recent National Academy of Engineering and National Research Council report: *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* I will also comment on the recent report of the American Physical Society, *The Hydrogen Initiative.*

At the outset I want to express the Department's appreciation for the valuable work performed by the National Research Council which conducted this very comprehensive study at our request. Its carefully considered recommendations and conclusions have already helped strengthen and focus DOE's hydrogen program and increased the likelihood of its success. The report will also help DOE better focus its research, priorities and funding, given the broad slate of potential hydrogen activities and technology directions. We are especially pleased to see the Committee's conclusion that "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."

Hydrogen Fuel Initiative

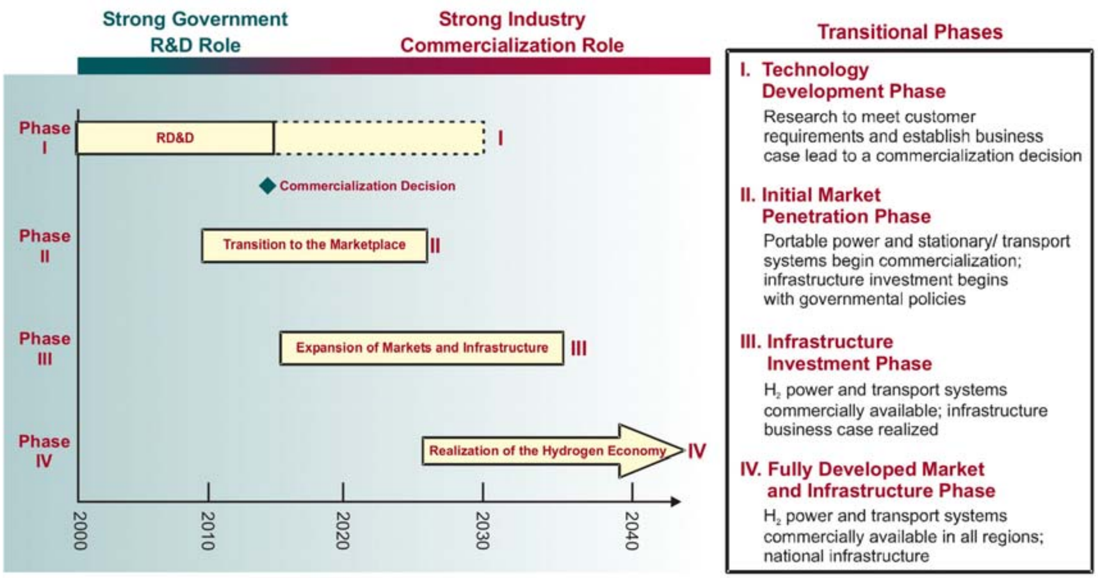
Mr. Chairman, it was a little more than one year ago that the President announced a pioneering plan to transform the Nation's energy future from one dependent on foreign petroleum to one that utilizes the most abundant element in the universe – hydrogen. This solution holds the potential to provide virtually limitless clean, safe, secure, affordable, and reliable energy from domestic resources. To achieve this vision, the President proposed that the federal government significantly increase its investment in hydrogen infrastructure research and development (R&D), including hydrogen production, storage, and delivery technologies, as well as fuel cells, with the goal of enabling an industry decision by 2015 to commercialize hydrogen fuel cell vehicles.

This vision is now shared around the world. Last fall, at the urging of Secretary Abraham, 15 nations, including the United States and the European Union, agreed to establish the International Partnership for the Hydrogen Economy (IPHE). The IPHE is providing a mechanism to efficiently organize and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy. The IPHE partners represent more than 85 percent of the world's gross domestic product and two thirds of the world's energy consumption and greenhouse gas emissions.

At a March 5, 2003 hearing before this Committee, I described in detail DOE's plans to help turn the concept of a hydrogen-based economy into reality. At the time we described how we would integrate our ongoing and future hydrogen R&D activities into a focused Hydrogen Program, and how we would integrate technology for hydrogen production (from fossil, nuclear, and renewable resources), infrastructure development (including delivery and storage), fuel cells, and other technologies. We also described how we would coordinate hydrogen activities within DOE and among the federal agencies to achieve the technical milestones on the road to a hydrogen economy.

We discussed the challenges to be faced and how we believed they could be met. We said that achieving a hydrogen-based economy would require a combination of technological breakthroughs, market acceptance, and large investments in a national hydrogen energy infrastructure. We knew that success would not happen overnight, or even over years, but rather over decades. We knew it would be a long-term process that would phase hydrogen in as the technologies and their markets are ready, and that success would require that the technologies to utilize hydrogen fuel and the availability of hydrogen fuel occur simultaneously.

Also at that hearing, I presented the following timeline:



As you can see, the timeline shows that we won't realize the full potential of a hydrogen economy for several decades. Phase I technology development will lead to a commercialization decision by industry only if government-sponsored and private research is successful in meeting customer requirements and in establishing a business case that can convince industry to invest. If industry makes a positive commercialization decision, we will be ready to take the next steps toward realizing the full potential of the hydrogen economy, a process that will evolve over several decades, and may include policy options other than research to catalyze infrastructure investment. The impact of hydrogen fuel cell vehicles will depend on how quickly the market introduces the new vehicles, the availability of production and delivery infrastructure, and the time it takes for a new fleet of hydrogen vehicles to replace the existing inventory of conventional vehicles.

Our focus today is the research and development to overcome the technical barriers associated with hydrogen and fuel cell technologies -- including lowering the cost of hydrogen production and fuel cell technologies, improving hydrogen storage systems, and developing codes and standards for hydrogen handling and use. The Department has requested $227 million in its FY 2005 budget request to support the Hydrogen Fuel Initiative. In addition, the Department of Transportation requested about $1.0 million.

Over the past year our progress has increased confidence that the 2015 goal is realistic and attainable. For example:

- Significant technical progress has been made in reducing the cost of hydrogen production. We have verified the ability to produce hydrogen from natural gas at $3.60 per gallon of gasoline equivalent from an integrated hydrogen refueling station that co-produces electricity from a stationary fuel cell. This meets our 2003 interim milestone.

- In the very near future, we will announce selections from two major competitive solicitations. The first is our hydrogen storage "Grand Challenge." Novel approaches, beyond pressurized tanks, are needed in the long term to provide the greater than 300 mile range that consumers expect. Our new hydrogen storage selections have established three "Centers of Excellence" where each center is composed of a national lab teamed with seven or eight universities to research novel materials for hydrogen storage.

- The second major solicitation is for our national fuel cell vehicle and hydrogen infrastructure "learning" demonstration. This “demonstration” is an extension of our research and will provide us the necessary data to focus our research on the most difficult technical barriers and safety issues, as well as help us identify vehicle-infrastructure interface issues that need to be worked out collectively by the government, automotive manufacturers and energy industry.

- In the coming months, we will also be announcing winners to our hydrogen production and delivery research solicitation.

To track the progress of our research, the Department and its industry partners jointly develop performance-based technical and cost milestones that reflect customer requirements and the business case needed for industry to invest. Our newly released Hydrogen Posture Plan details the Department's overall integrated plan, identifies key technology milestones, and includes timelines that provide clear and quantifiable measures to track and demonstrate progress. We do not believe that these milestones are unrealistic. They are, however, intentionally aggressive so that we “set the bar high” to try to stimulate revolutionary ideas in research. Having said that, we plan to evaluate all of the milestones based on the National Academies’ report. Indeed, the Hydrogen Posture Plan already takes into account many of the report’s comments.

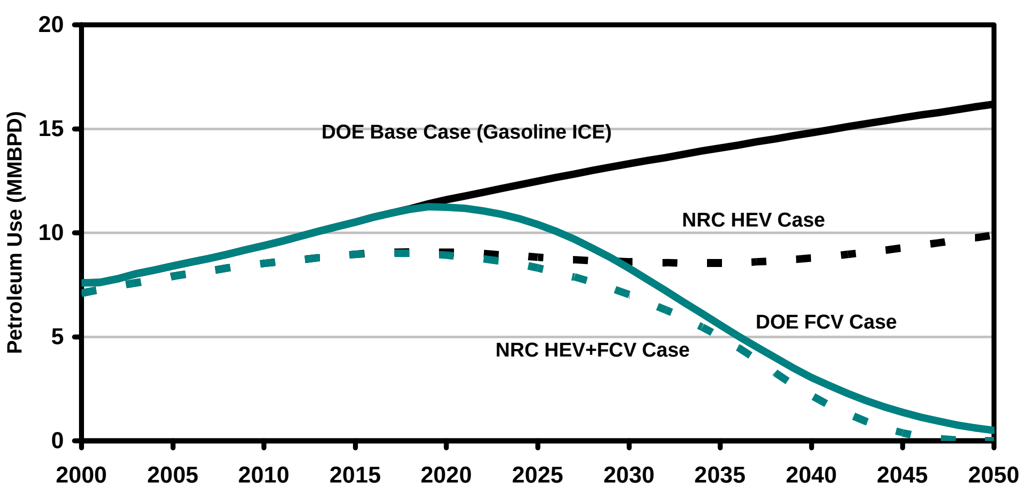
Our focus on hydrogen fuel cell vehicles does not come at the expense of support for conservation and gasoline hybrid vehicles as short-term strategy for reducing oil use, criteria pollutants and greenhouse gas emissions. Under the FreedomCAR Partnership, in addition to research on fuel cells, the Department requests $91 million to continue research to develop advanced, affordable hybrid component technologies. These technologies include energy storage devices, power electronics, lightweight materials, advanced combustion engines, and other technologies that have application for the gasoline hybrids of today, the fuel cell vehicles of tomorrow, or in many cases, both. The Department continues to implement robust programs in support of wind turbines, solar photovoltaic technology, Generation IV nuclear power systems, and solid state lighting, and many other energy technology program areas.

However, as the National Academies' report notes, it will take a revolutionary approach like hydrogen fuel cells to provide the fundamental change that will allow us to be completely independent of oil and free of carbon in the tailpipe. Incremental changes available in the near term will not overcome the increasing demands for a limited supply of oil.

This is demonstrated in the chart titled "Oil Use by Light Duty Vehicles." The National Academies' National Research Council report shows a case where gasoline hybrid electric vehicles (HEV), the "NRC HEV Case," penetrate the market. As you can see, under this scenario, petroleum use stays constant at best and we don't reduce our vulnerabilities associated with importing foreign oil since domestic production stays constant. When you consider the growth of petroleum use around the world, especially in developing countries, there will be an even greater demand for limited supplies.

Fuel cell vehicle (FCV) market penetration scenarios developed by DOE and the National Academies' National Research Council (NRC) are similar. As shown in the chart, the petroleum use from the "DOE FCV" case is very similar to the "NRC HEV + FCV" case. This analysis also shows that in the long-term, increased fuel economy alone will not even reduce the amount of oil use compared to today's level. Simply put, if we are going to significantly reduce our dependence on foreign oil, we need to substitute for petroleum.

Oil Use by Light-Duty Vehicles



Response to National Academies Report

DOE fully recognized the complexity and uncertainties involved in a transition to a hydrogen economy, and requested the National Academies to conduct an independent review of our hydrogen production and infrastructure options. We requested assistance in two major areas: (1) assessing strategies for hydrogen production from domestic resources in near-, mid-, and long-term; and (2) reviewing the Department's current research plans and making recommendations on research strategies.

Last April, the committee provided us with four interim recommendations, which we acted upon immediately. They are:

1. **The Department should establish an independent systems engineering and analysis group**. In response to this recommendation we conducted a nationwide recruiting effort and hired a lead systems integrator. The systems integrator has been tasked to develop a model to assess the impact of various technology pathways, identify key cost drivers and technological gaps, and assist in prioritization of R&D directions. A portion of the increase in the FY 2005 budget request will be used to create this capability.

2. **The Department should give exploratory and fundamental research additional budgetary emphasis.** As a result of this recommendation, the DOE Office of Science is now directly involved in supporting the President's Hydrogen Fuel Initiative. Last May, the Office of Science hosted a workshop to identify the basic research needs for a hydrogen economy. The Office of Science created and filled a position for Senior Advisor for Applied Energy Programs. This person has a broad knowledge of the Science R&D programs at the National Laboratories, and helps the applied programs in their search for technological breakthroughs. The Department's FY 2005 budget request includes $29 million for the Office of Science to conduct basic research in hydrogen production, storage and use.

3. **DOE should make a significant effort to address safety issues**. In response, we developed guidelines for safety plans to be carried out on all projects and established a safety review panel to evaluate implementation of these plans. In addition, the Department's FY 2005 budget request includes a three-fold increase in funding for safety-related research. We have also worked closely with the Department of Transportation, the National Institute of Science and Technology, and other organizations to define roles and responsibilities for the research and development of hydrogen codes and standards to enable safe use of hydrogen.

4. **DOE should integrate hydrogen R&D efforts across the applied energy programs, the Office of Science, and appropriate industry partners.** The Department's Hydrogen Posture Plan integrates the hydrogen activities supporting the President's Hydrogen Fuel Initiative across the renewable energy, fossil energy, science, and nuclear energy offices. This plan lays the foundation for a coordinated response to the President's goal for accelerated research on critical path hydrogen and fuel cell technologies. We have also expanded our existing FreedomCAR

Partnership to include major energy companies (ExxonMobil, ConocoPhillips, ChevronTexaco, BP and Shell) along with all three major U.S. auto manufacturers.

The final report of the committee presented us with two main themes:

Theme 1: There should be a shift away from some development areas towards more exploratory work.

The Department has already begun shifting towards more exploratory research. A good example is in the hydrogen storage area, where we are establishing three "Centers of Excellence" led by national laboratories along with multiple university and industry partners. This could be a model for "expert" centers focusing on other priority research areas such as fuel cell costs and durability, distributed hydrogen production costs and efficiency, systems analysis for hydrogen delivery, and renewable hydrogen production methods such as photobiological, photo-electrochemical (direct solar conversion) and thermochemical (splitting water with heat processes).

The Department's mix of funding according to OMB circular A-11 for the FY 2005 budget request is as follows:

Basic Research:	12.9%
Applied Research:	42.5%
Development:	29.2%
Demonstration:	13.4%
Deployment:	2.0%

This mix reflects our shift towards more exploratory R&D in the hydrogen storage area. We are currently evaluating our fuel cell cost and durability research to see if more exploratory R&D is appropriate. I want to caution everyone that "exploratory" R&D is not synonymous with "basic" R&D. We believe the committee is recommending that we shift away from some development work that industry is capable of doing.

Theme 2: The hydrogen transition may best be accomplished through distributed production at fueling sites, from natural gas reforming or water electrolysis from wind or solar energy. The committee recommends increased R&D investments on these distributed hydrogen technologies, which will supply hydrogen for the early transitional period, and suggests allowing the long-term hydrogen economy to evolve.

Based on this recommendation, the Department will increase its focus on exploratory research to reduce costs and increase efficiency of water electrolysis and distributed natural gas reforming. In this recommendation, we believe the National Academies' committee is telling us not to over manage the long term, that the longer-term hydrogen economy should "evolve" through greater emphasis on breakthroughs in technologies with longer time horizons for commercial application, such as carbon capture and sequestration to enable coal as a long-term resource, photoelectrochemical, photobiological, and thermochemical methods.

In keeping with this recommendation, the Office of Science is now established as a direct participant in the President's initiative and we are directing our applied research into more exploratory technologies. As mentioned earlier, our hydrogen storage "Grand Challenge" will create three Centers of Excellence involving federal laboratories, universities, and private industry. We agree with the need to support exploratory research and will shift our program activities to a more basic and exploratory nature, as appropriate.

Response to American Physical Society Report

The American Physical Society report on hydrogen calls for more spending on basic research and contends that demonstrations are premature. On the second part of this recommendation, DOE along with its industry partners believe there is a clear need for such "learning" demonstrations. These demonstrations serve as extensions of our research, and are aimed at obtaining performance and durability data in real world environments. I want to stress that these are not demonstrations geared toward commercialization. There is no formula that can tell us that we have achieved a certain percentage of our target and that it is now time to conduct a demonstration to close the final gap. At this stage in the development, technology costs are reduced through research breakthroughs in materials, performance, and manufacturing technology, not "commercial" demonstrations.

Learning demonstrations, however, will provide improved understanding of the impact of various climatic conditions on fuel cell performance and durability. Such data are crucial to resolving system barriers such as water and heat management within the fuel cell. At the conclusion of the 5-year demonstration program, the pre-established targets of 2,000 hours durability, 250 mile range and $3.00 per gallon gasoline equivalent are to be met by industry. This demonstration effort will give us the statistical evidence that adequate progress is being made to meet the 2015 criteria of 5,000 hours durability, 300 mile range and $1.50-2.00 per gallon gasoline equivalent. These demonstrations will provide accelerated data that we will need to refocus our future R&D, and will provide the hard data needed to make difficult decisions should we experience a lack of research progress.

In a hydrogen economy, we will need multiple and complex interfaces among production, delivery, storage, conversion and end-use. Auto manufacturers, energy companies, and component suppliers will need to work together over the next several years to resolve such issues as the vehicle-infrastructure refueling interfaces. If we are going to make the huge transformation to a hydrogen energy system, it will be private companies, not the government, to make the investment and build the automotive manufacturing infrastructure and hydrogen production and delivery infrastructure. This learning demonstration will reveal potential solutions to overcoming technical and economic hurdles to building infrastructure

The learning demonstration will also reveal potential safety issues and open a door to cooperation with local jurisdictions on uniform codes and standards. In summary, we believe that limited learning demonstrations, utilizing less than 15 percent of the overall hydrogen program budget and with industry cost-sharing at a 1:1 ratio, will provide us with the practical experience and critical data to ensure that our applied and exploratory research efforts are focused on the right problems.

Conclusion

Mr. Chairman, all the panelists here today will agree that achieving the vision of the hydrogen energy future is a great challenge. It will require careful planning and coordination, public education, technology development, and substantial public and private investments. It will require a broad political consensus and a bipartisan approach. Most of all, it will take leadership and resolve. By being bold and innovative, we can change the way we do business here in America; we can change our dependence upon foreign sources of energy; we can help with the quality of the air; and we can make a fundamental difference for the future of our children. This Committee in particular has been instrumental in providing that kind of leadership over the years, and we look forward to continuing this dialogue in the months and years ahead.

We at the Department of Energy welcome the challenge and opportunity to play a vital role in this Nation's energy future and to support our national security in such a fundamental way. This completes my prepared statement. I would be happy to answer any questions you may have.

THE HYDROGEN ECONOMY: OPPORTUNITIES, COSTS, BARRIERS, AND R&D NEEDS

Written Statement of

Michael P. Ramage
Chairman of the Committee on Alternatives and Strategies for Future Hydrogen Production and Use
National Research Council of the National Academies
National Academy of Engineering
and
Executive Vice President, ExxonMobil Research and Engineering (retired)

before the

Committee on Science
U.S. House of Representatives

MARCH 3, 2004

Mr. Chairman and Members of the Committee:

My name is Michael Ramage and I served as Chairman of the National Research Council Committee on Alternatives and Strategies for Future Hydrogen Production and Use. The Research Council–known as the NRC–is the operating arm of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine, chartered by Congress in 1863 to advise the government on matters of science and technology. The 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[1] 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.

[1]The committee's final report—The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs—was released in February, 2004 and is available at www.nap.edu.

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.[2] 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 laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."[3] 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

[2]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.

[3]Weekly Compilation of Presidential Documents. Volume 39, Number 5. p. 111. Monday, February 3, 2003. Government Printing Office: Washington, D.C.

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 hydrogen 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 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 byproduct 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 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.

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[4] 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 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, 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,

[4] 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.

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 mid-century.

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, are short of required durability, and 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)[5] before fuel cell vehicles (FCVs) become a plausible commercial option, and 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; 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 to the high volume production of fuel cell vehicles.

[5]Cost includes fuel cell module, precious metals, fuel processor, compressed hydrogen storage, balance of plant, and assembly, labor and depreciation.

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 attack 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 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 DOE 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 (R&D) 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:

- Safety policy goals should be proposed and discussed by 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.
- The 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 (kW), 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," (DOE, 2003b) dated June 3, 2003. 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 & 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 capture 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. A general budget is contained in the Appendix for the plan, but the plan provides no dollar numbers at the project level, even for existing projects/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 (Pub. 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[6]—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

[6] Secretary 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.

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 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;
- *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.

COMMITTEE ON ALTERNATIVES AND STRATEGIES FOR FUTURE HYDROGEN PRODUCTION AND USE

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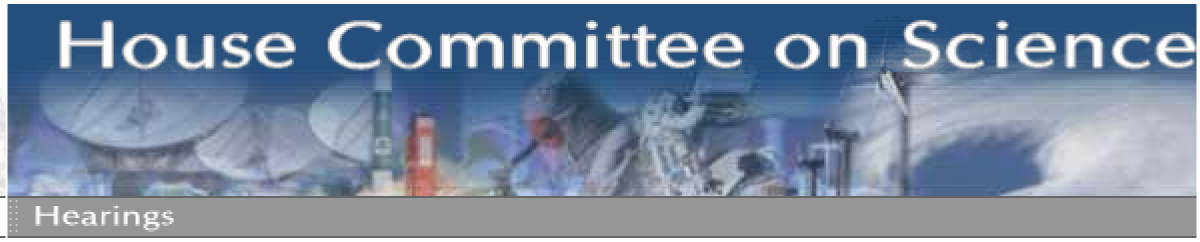

Testimony before the House Science Committee
March 3, 2pm
Peter Eisenberger, Columbia University

Mr. Chairman, Mr. Gordon, members of the Committee, thank you for the invitation to testify today.

In January 2003, President Bush announced an Initiative to reduce the nation's dependence on foreign oil through the production of hydrogen fuel and a hydrogen-fueled car. The Initiative envisions the competitive use of hydrogen in commercial transportation by the year 2020.

I chaired a committee of the American Physical Society that analyzed this Initiative - we released our report on Monday. The bottom line is that major scientific breakthroughs are required for the Hydrogen Initiative to succeed. We made several management and funding recommendations that, in our opinion, will increase the chances for long-term success.

Before I get into the specifics, let me say a very brief word about our authors and methodology. Together, the authors and reviewers have considerable experience in bench science, the management of industrial technolo grams from the laboratory to systems level, management of government R&D programs, and the economic of energy-commercialization programs. We did not carry out a new analysis of the scientific elements of the Hydrogen Initiative. Instead, we distilled the considerable work that is already available. Our sources included the DOE "Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use", the Hydrogen Energy Roadmap, and numerous presentations by government officials managing the Hydrogen Initiative, including those for the just released NRC report.

As a starting point, let me say that currently there is only a very nascent technology base upon which to build a hydrogen economy. Currently, the US industry provides hydrogen to meet the needs of the non-transportation sector that is only about 3% of what is needed for the transportation sector. Several hydrogen-fueling stations are scheduled to open this year. And several models of hydrogen-fueled cars have been demonstrated. But, none of the current technologies are competitive options for the consumer.

The most promising hydrogen-engine technologies require 10 to 100 times improvements in cost or performan in order to be competitive. As the Secretary of Energy has stated, current hydrogen production methods are fo times more expensive than gasoline, and significant challenges remain to satisfy both energy security and environmental objectives of converting to a hydrogen-based transportation sector. Finally, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

These are very large performance gaps. And our committee concluded that incremental improvements to existing technologies are not sufficient to close all the gaps. In particular, hydrogen storage is the potential sho stopper.

Simply put, for the Hydrogen Initiative to succeed, major scientific breakthroughs are needed. This will not be easy. We cannot simply engineer our way to a hydrogen economy. But, we can take several steps now to mak success more likely.

Without question, relevant basic science must have greater emphasis in both the planning and the research program of the Hydrogen Initiative. This is not a controversial conclusion. The Bush Administration has already taken steps in this direction, but, more must be done. We recommend that:

1. The Hydrogen Technical Advisory Committee include members with strong research backgrounds who are familiar with the key basic science problems.
2. Principal-Investigator basic research should be increased. And this PI research should be complemented wi competitively-bid, peer-reviewed multidisciplinary research centers that carry out basic research in the key research areas of production, storage and use. These university-based centers should have active industry an national laboratory participation.

The issue of funding is, of course, a delicate one. Resources are not unlimited and members of your committee face difficult decisions. Several members of our APS committee have managed large-scale industrial technolog programs. As for myself, in an earlier life, I was Senior Director of the Corporate Research Laboratory for Exxo For what it's worth, I and the members of my committee, feel your pain. We have faced difficult funding decisio in our careers.

Perhaps the most useful thing I can share with you is the manner in which industries approaches these difficult funding decisions. The main factors involve technological competitiveness and readiness, market acceptance, and rate of penetration. In the case of Congress, one needs to add the criteria of meeting national security objectives. Our evaluation is that for hydrogen there are very significant technology gaps, a lack of an existing infrastructure and the inevitable slow rate of penetration for a new energy technology. This means that one would invest more resources in research and less, if at all, in development projects. Pilot projects to demonstra specific components like sequestration are more appropriate at this stage of the Hydrogen Initiative. Premature investments in a large demonstration projects have a history of not only failing but also damaging the overall objectives.

However, national security objectives may argue for a more aggressive development plan than industry would follow, though premature large-scale demonstration projects are unlikely to be helpful. In this regard, I will mention one additional point of view that the industrial managers on our APS committee all shared - hedging.

In the event that the timeline for significant hydrogen vehicles market penetration slips beyond 2020, there cou be, for energy security reasons, a greater need for technologies that serve as a "bridge" between the current fossil-fuel economy and any future hydrogen economy. Also the likelihood is increased that continued investment in research will produce new discoveries that will identify a far superior way to meet our needs in th long term. Increasing the focus on basic science and engineering that advances such technologies would serv as a sensible hedge and at the same time maintain the development of technologies that show clear short-term promise.

Similarly, the Hydrogen Initiative must not displace research into promising energy efficiency and renewable energy areas, and carbon sequestration. These investments both complement and contribute to the goals of a hydrogen economy. And, they become increasingly important means for reducing CO_2 and enhancing our energy security in the event that the significant technology hurdles for the Initiative are not met within the proposed timeline.

I hope that our perspective and our recommendations help in your oversight of the Hydrogen Initiative.

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TESTIMONY

For the Hearing

Reviewing the Hydrogen Fuel and FreedomCAR Initiatives

SUBMITTED
TO
THE HOUSE SCIENCE COMMITTEE

BY

DR. JOSEPH ROMM

Author, *The Hype about Hydrogen* (Island Press, March 2004)

Former Acting Assistant Secretary of Energy

March 3, 2004

Mr. Chairman and esteemed members of the Science Committee, I thank you for the opportunity to submit this testimony. I wish to express my appreciation for the strong support this committee has shown for clean energy technology R&D over the course of several decades.

Hydrogen and fuel cell cars are being hyped today as few technologies have ever been. In his January 2003 State of the Union address, President Bush announced a $1.2 billion research initiative, "so that the first car driven by a child born today could be powered by hydrogen, and pollution-free." The April 2003 issue of *Wired* magazine proclaimed, "How Hydrogen can save America." In August 2003, General Motors said that the promise of hydrogen cars justified delaying fuel-efficiency regulations.

Yet, for all the hype, a number of recent studies raise serious doubts about the prospects for hydrogen cars. In February 2004, a prestigious National Academy of Sciences panel concluded, "In the best-case scenario, the transition to a hydrogen economy would take many decades, and any reductions in oil imports and carbon dioxide emissions are likely to be minor during the next 25 years." And that's the best case. Realistically, as I discuss in my new book *"The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate,"* a major effort to introduce hydrogen cars before 2030 would undermine efforts to reduce emissions of heat-trapping greenhouse gases like carbon dioxide—the main culprit in last century's planet-wide warming of 1 degree Fahrenheit.

As someone who helped oversee the Department of Energy's program for clean energy, including hydrogen, for much of the 1990s—during which time we increased hydrogen funding by a factor of ten with the support of the Committee—I believe that continued research into hydrogen remains important because of its potential to provide a pollution-free substitute for oil in the second half of this century. But if we fail to limit greenhouse gas emissions over the next decade—and especially if we fail to do so because we have bought into the hype about hydrogen's near-term prospects—we will be making an unforgivable national blunder that may lock in global warming for the U.S. of 1 degree Fahrenheit *per decade* by mid-century.

HYDROGEN and FUEL CELLS

Hydrogen is not a readily accessible energy source like coal or wind. It is bound up tightly in molecules like water and natural gas, so it is expensive and energy-intensive to extract and purify. A hydrogen economy—which describes a time when the economy's primary energy carrier is hydrogen made from sources of energy that have no net emissions of greenhouse gases—rests on two pillars: a pollution-free source for the hydrogen itself and a fuel cell for efficiently converting it into useful energy without generating pollution.

Fuel cells are small, modular, electrochemical devices, similar to batteries, but which can be continuously fueled. For most purposes, you can think of a fuel cell as a "black box" that takes in hydrogen and oxygen and puts out only water plus electricity and heat.

The most promising fuel cell for transportation is the Proton Exchange Membrane (PEM) fuel cell, first developed in the early 1960s by General Electric for the Gemini space program. The price goal for transportation fuel cells is to come close to that of an internal combustion engine, roughly $30 per kilowatt. Current PEM costs are about 100 times greater. It has taken wind power and solar power each about twenty years to see a tenfold decline in prices, after major government and private-sector investments in R&D, and they still each comprise well under 1% of US electricity generation. A major technology breakthrough is needed in transportation fuel cells before they will be practical.

THE STORAGE SHOW-STOPPER?

Running a fuel cell car on pure hydrogen, the option now being pursued most automakers and fuel cell companies, means the car must be able to safely, compactly, and cost-effectively store hydrogen onboard. This is a major technical challenge. At room temperature and pressure, hydrogen takes up some 3,000 times more space than gasoline containing an equivalent amount of energy. The Department of Energy's 2003 *Fuel Cell Report to Congress* notes:

> Hydrogen storage systems need to enable a vehicle to travel 300 to 400 miles and fit in an envelope that does not compromise either passenger space or storage space. Current energy storage technologies are insufficient to gain market acceptance because they do not meet these criteria.

The most mature storage options are liquefied hydrogen and compressed hydrogen gas.

Liquid hydrogen is widely used today for storing and transporting hydrogen. Liquids enjoy considerable advantages over gases from a storage and fueling perspective: They have high energy density, are easier to transport, and are typically easier to handle. Hydrogen, however, is not typical. It becomes a liquid only at -423 °F, just a few degrees above absolute zero. It can be stored only in a super-insulated cryogenic tank.

Liquid hydrogen is exceedingly unlikely to be a major part of a hydrogen economy because of the cost and logistical problems in handling liquid hydrogen and because liquefaction is so energy intensive. Some 40% of the energy of the hydrogen is required to liquefy it for storage. Liquefying one kg of hydrogen using electricity from the U.S. grid would by itself release some 18 to 21 pounds of carbon dioxide into the atmosphere, roughly equal to the carbon dioxide emitted by burning one gallon of gasoline.

Compressed hydrogen storage is used by nearly all prototype hydrogen vehicles today. Hydrogen is compressed up to pressures of 5,000 pounds per square inch (psi) or even 10,000 psi in a multistage process that requires energy input equal to 10% to 15% of the hydrogen's usable energy content. For comparison, atmospheric pressure is about 15 psi.

Working at such high pressures creates overall system complexity and requires materials and components that are sophisticated and costly. And even a 10,000-psi tank would take up 7 to 8 times the volume of an equivalent-energy gasoline tank or perhaps four times the volume for a comparable range (since the fuel cell vehicle will be more fuel efficient than current cars).

The National Academy study concluded that both liquid and compressed storage have "little promise of long-term practicality for light-duty vehicles" and recommended that DOE halt research in both areas. Practical hydrogen storage requires a major technology breakthrough, most likely in solid-state hydrogen storage.

AN UNUSUALLY DANGEROUS FUEL

Hydrogen has some safety advantages over liquid fuels like gasoline. When a gasoline tank leaks or bursts, the gasoline can pool, creating a risk that any spark would start a fire, or it can splatter, posing a great risk of spreading an existing fire. Hydrogen, however, will escape quickly into the atmosphere as a very diffuse gas. Also, hydrogen gas is non-toxic.

Yet, hydrogen has its own major safety issues. It is highly flammable with an ignition energy 20 times smaller than that of natural gas or gasoline. It can be ignited by cell phones and electrical storms located miles away. Hence, leaks pose a significant fire hazard. At the same time, it is one of the most leak-prone of gases. Odorants like sulfur are impractical, in part because they poison fuel cells. Hydrogen burns nearly invisibly, and people have unwittingly stepped into hydrogen flames. Hydrogen can cause many metals, including the carbon steel widely used in gas pipelines, to become brittle. In addition, any high-pressure storage tank presents a risk of rupture. For these reasons, hydrogen is subject to strict and cumbersome codes and standards, especially when used in an enclosed space where a leak might create a growing gas bubble.

Some 22% or more of hydrogen accidents are caused by undetected hydrogen leaks. This "despite the special training, standard operating procedures, protective clothing, electronic flame gas detectors provided to the limited number of hydrogen workers," as Russell Moy, former group leader for energy storage programs at Ford Motors has wrote in the November 2003 *Energy Law Journal*. Moy concludes "with this track record, it is difficult to imagine how hydrogen risks can be managed acceptably by the general public when wide-scale deployment of the safety precautions would be costly and public compliance impossible to ensure." Thus, major innovations in safety will be required before a hydrogen economy is practical.

AN EXPENSIVE FUEL

A key problem with the hydrogen economy is that pollution-free sources of hydrogen are unlikely to be practical and affordable for decades. Indeed, even the pollution-generating means of making hydrogen are currently too expensive and too inefficient to substitute for oil.

Natural gas (methane or CH_4) is the source of 95% of U.S. hydrogen. The overall energy efficiency of the steam methane reforming process (the ratio of the energy in the hydrogen output to the energy in the natural gas fuel input) is about 70%.

According to a comprehensive 2002 analysis for the National Renewable Energy Laboratory by Dale Simbeck and Elaine Chang, the cost of producing and delivering hydrogen from natural gas, or producing hydrogen on-site at a local filling station, is $4 to $5 per kilogram (without adding in any fuel taxes), comparable to a price of gasoline of $4-$5 a gallon (since a kilogram of hydrogen contains about the same usable energy as a gallon of gasoline). This is over three times the current untaxed price of gasoline. Considerable R&D is being focused on efforts to reduce the cost of producing hydrogen from natural gas, but fueling a significant fraction of U.S. cars with hydrogen made from natural gas makes little sense, either economically or environmentally, as discussed below.

Water can be electrolyzed into hydrogen and oxygen. This process is extremely energy-intensive. Typical commercial electrolysis units require about 50 kiloWatt-hours (kWh) per kilogram, an energy efficiency of 70%. The cost today of producing and delivering hydrogen from a central electrolysis plant is estimated at $7 to $9 per kilogram. The cost of on-site production at a local filling station is estimated at $12 per kg. Replacing one half of U.S. ground transportation fuels in 2025 (mostly gasoline) with hydrogen from electrolysis would require about *as much electricity as is sold in the U.S. today*.

From the perspective of global warming, electrolysis makes little sense for the foreseeable future. Burning a gallon of gasoline releases about 20 pounds of carbon dioxide. Producing 1 kg of hydrogen by electrolysis would generate, on average, 70 pounds of carbon dioxide. Hydrogen could be generated from renewable electricity, but that would be even more expensive and, as we will see, renewable electricity has better uses for the next few decades.

Other greenhouse-gas-free means of producing hydrogen are being pursued. The Department of Energy's FutureGen project is aimed at designing, building, and constructing a 270-megawatt prototype coal plant that would cogenerate electricity and hydrogen while removing 90% of the carbon dioxide. The goal is to validate the viability of the system by 2020. If a permanent storage location can be found for the carbon dioxide, such as an underground reservoir, this would mean that coal could be a virtually carbon-free source of hydrogen. The Department is also pursuing thermochemical hydrogen production systems using nuclear power with the goal of demonstrating commercial scale production by 2015. Biomass (plant matter) can be gasified and converted into hydrogen in a process similar to coal gasification. The cost of delivered hydrogen from gasification of biomass has been estimated at $5 to $6.30 per kg. It is unlikely that any of these approaches could provide large-scale sources of hydrogen at competitive prices until after 2030.

Stranded investment is one of the greatest risks faced by near-term hydrogen production technologies. For instance, if over the next two decades we built a hydrogen infrastructure around small methane reformers in local fueling stations, and then decided that U.S. greenhouse gas emissions must be dramatically reduced, we would have to replace that infrastructure almost entirely. John Heywood, director of the Sloan Automotive Lab at the Massachusetts Institute of Technology, argues, “If the hydrogen does not come from renewable sources, then it is simply not worth doing, environmentally or economically.” A major technology breakthrough will be needed to deliver low-cost, zero-carbon hydrogen.

THE CHICKEN-AND-EGG PROBLEM

Bernard Bulkin, Chief Scientist for British Petroleum, discussed BP’s experience with its customers at the National Hydrogen Association annual conference in March 2003. He said, “if hydrogen is going to make it in the mass market as a transport fuel, it has to be available in 30 to 50% of the retail network from the day the first mass manufactured cars hit the showrooms.” Yet, a 2002 analysis by Argonne National Laboratory found that even with improved technology, “the hydrogen delivery infrastructure to serve 40% of the light duty fleet is likely to cost over $500 billion.” Major breakthroughs in both hydrogen production and delivery will be required to reduce that figure significantly.

Another key issue is the chicken-and-egg problem: Who will spend the hundreds of billions of dollars on a wholly new nationwide infrastructure to provide ready access to hydrogen for consumers with fuel-cell vehicles until millions of hydrogen vehicles are on the road? Yet who will manufacture and market such vehicles until the infrastructure is in place to fuel those vehicles? And will car companies and fuel providers be willing to take this chance before knowing whether the public will embrace these cars? I fervently hope to see an economically, environmentally, and politically plausible scenario for how this classic Catch-22 chasm can be bridged; it does not yet exist.

Centralized production of hydrogen is the ultimate goal. A pure hydrogen economy requires that hydrogen be generated from carbon-dioxide-free sources, which would almost certainly require centralized hydrogen production closer to giant wind-farms or at coal/biomass gasification power plants where carbon dioxide is extracted for permanent underground storage. That will require some way of delivering massive quantities of hydrogen to tens of thousands of local fueling stations.

Tanker trucks carrying liquefied hydrogen are commonly used to deliver hydrogen today, but make little sense in a hydrogen economy because of liquefaction’s high energy cost. Also, few automakers are pursuing onboard storage with liquid hydrogen. So after delivery, the fueling station would still have to use an energy-intensive pressurization system. This might mean that storage and transport alone would require some 50% of the energy in the hydrogen delivered, negating any potential energy and environmental benefits from hydrogen.

Pipelines are also used for delivering hydrogen today. Interstate pipelines are estimated to cost $1 million per mile or more. Yet, we have very little idea today what hydrogen-generation processes will win in the marketplace over the next few decades—or whether hydrogen will be able to successfully compete with future high-efficiency vehicles, perhaps running on other pollution-free fuels. This uncertainty makes it unlikely anyone would commit to spending tens of billions of dollars on hydrogen pipelines before there are very high hydrogen flow rates transported by other means, and before the winners and losers in both the production end and the vehicle end of the marketplace have been determined. In short, pipelines are unlikely to be the main hydrogen transport means until the post-2030 period.

Trailers carrying compressed hydrogen canisters are a flexible means of delivery, but are relatively expensive because hydrogen has such a low energy density. Even with technology advances, a 40-metric-ton truck might deliver only about 400 kg of hydrogen into onsite high-pressure storage. A 2003 study by ABB researchers found that for a delivery distance of 300 miles, the delivery energy approaches 40% of the usable energy in the hydrogen delivered. Without dramatic improvement in high-pressure storage systems, this approach seems impractical for large-scale hydrogen delivery.

Producing hydrogen on-site at local fueling stations is the strategy advocated by those who want to deploy hydrogen vehicles in the next two decades. On-site electrolysis is impractical for large-scale use because it would be highly expensive and inefficient, while generating large amounts of greenhouse gases and other pollutants. The hydrogen would need to be generated from small methane reformers. Although onsite methane reforming seems viable for limited demonstrations and pilots, it is also both impractical and unwise for large-scale application, for a number of reasons.

First, the upfront cost is very high—more than $600 billion just to provide hydrogen fuel for 40% of the cars on the road, according to Argonne. A reasonable cost estimate for the initial hydrogen infrastructure, derived from Royal Dutch/Shell figures, is $5000 per car.

Second, the cost of the delivered hydrogen itself in this option is also higher than for centralized production. Not only are the small reformers and compressors typically more expensive and less efficient than larger units, but they will likely pay a much higher price for the electricity and gas to run them. A 2002 analysis put the cost at $4.40 per kg (that is, equal to $4.40 per gallon of gasoline).

Third, "the risk of stranded investment is significant, since much of an initial compressed hydrogen station infrastructure could not be converted later if either a non-compression hydrogen storage method or liquid fuels such as a gasoline-ethanol combination proved superior" for fuel-cell vehicles." This was the conclusion of a major 2001 study for the California Fuel-Cell Partnership, a Sacramento-based public-private partnership to help commercialize fuel cells. Most of a methane-based investment would also likely be stranded once the ultimate transition to a pure hydrogen economy was made, since that would almost certainly rely on centralized production and not make use of small methane reformers. Moreover, it's possible the entire investment would be stranded in the scenario where hydrogen cars simply never achieve the combination of popularity, cost, and performance to triumph in the marketplace.

In the California analysis, it takes 10 years for investment in infrastructure to achieve a positive cash flow, and to achieve this result requires a variety of technology advances in both components and manufacturing. Also, even a small tax on hydrogen (to make up the revenue lost from gasoline taxes) appears to delay positive cash flow indefinitely. The high-risk and long-payback nature of this investment would seem far too great for the vast majority of investors, especially given alternative fuel vehicles history.

The U.S. has a great deal of relevant experience in the area of alternative fuel vehicles that is often ignored in discussions about hydrogen. The 1992 Energy Policy Act established the goal of having alternative fuels replace at least 10% of petroleum fuels in 2000, and at least 30% in 2010. By 1999, some one million alternative fuel vehicles were on the road, only about 0.4% of all vehicles. A 2000 General Accounting Office report explained the reasons for the lack of success:

> Fundamental economic impediments—such as *the relatively low price of gasoline, the lack of refueling stations for alternative fuels, and the additional cost to purchase these vehicles*—explain much of why both mandated fleets and the general public are disinclined to acquire alternative fuel vehicles and use alternative fuels.

It seems likely that all three of these problems will hinder hydrogen cars. Compared to other alternative fuels (such as ethanol and natural gas), the best analysis today suggests hydrogen will have a much higher price for the fuel, the fueling stations, and the vehicles.

The fourth reason that producing hydrogen on-site from natural gas at local fueling stations is impractical is that natural gas is simply the wrong fuel on which to build a hydrogen-based transportation system:

- The U.S. consumes nearly 23 trillion cubic feet (tcf) of natural gas today and is projected to consume more than 30 tcf in 2025. Replacing 40% of ground transportation fuels with hydrogen in 2025 would probably require an *additional* 10 tcf of gas (plus 300 *billion* kwh of electricity—10% of current power usage). Politically, given the firestorm over recent natural gas supply constraints and price spikes, it seems very unlikely the U.S. government and industry would commit to natural gas as a substitute for even a modest fraction of U.S. transportation energy.
- Much if not most incremental U.S. natural gas consumption for transportation would likely come from imported liquefied natural gas (LNG). LNG is dangerous to handle and LNG infrastructure is widely viewed as a likely terrorist target. Yet one of the major arguments in favor of alternative fuels has been their ability to address concerns over security and import dependence.
- Finally, natural gas has too much economic and environmental value to the electric utility, industrial, and buildings sectors to justify diverting significant quantities to the transportation sector, thereby increasing the price for all users. In fact, using natural gas to generate significant quantities of hydrogen for transportation would, for the foreseeable future, undermine efforts to combat global warming (as discussed below).

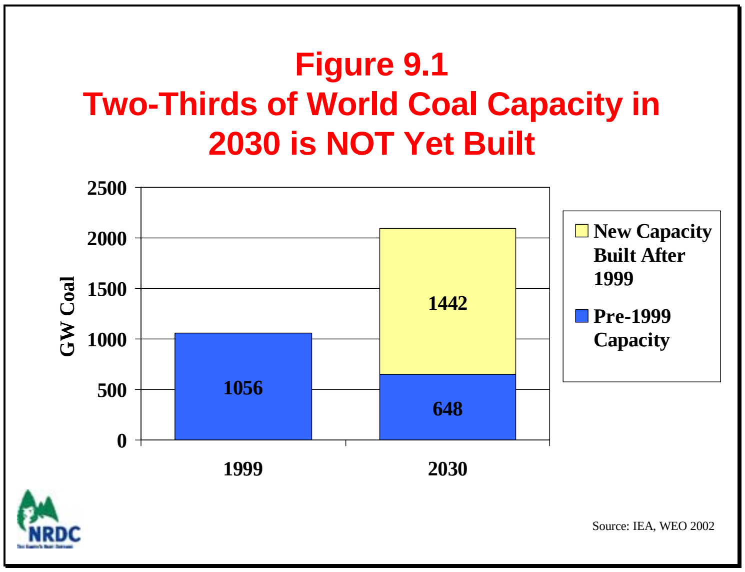
Thus, beyond limited pilot stations, it would be unwise to build thousands of local refueling stations based on steam methane reforming (or, for that matter, based on any technology not easily adaptable to delivery of greenhouse-gas-free hydrogen).

THE GLOBAL WARMING CENTURY

Perhaps the ultimate reason hydrogen cars are a post-2030 technology is the growing threat of global warming. Our energy choices are now inextricably tied to the fate of our global climate. The burning of fossil fuels—oil, gas and coal—emits carbon dioxide (CO_2) into the atmosphere where it builds up, blankets the earth and traps heat, accelerating global warming. We now have greater concentrations of CO_2 in the atmosphere than at any time in the past 420,000 years, and probably anytime in the past 3 million years—leading to rising global temperatures, more extreme weather events (including floods and droughts), sea level rise, the spread of tropical diseases, and the destruction of crucial habitats, such as coral reefs.

Carbon-emitting products and facilities have a very long lifetime: Cars last 13 to 15 years or more, coal plants can last 50 years. Also, carbon dioxide lingers in the atmosphere trapping heat for more than a century. These two facts together create an urgency to avoid constructing another massive and long-lived generation of energy infrastructure that will cause us to miss the window of opportunity for carbon-free energy until the next century.

Between 2000 and 2030, the International Energy Agency (IEA) projects that coal generation will double. The projected new plants would commit the planet to total carbon dioxide emissions of some 500 billion metric tons over their lifetime, which is roughly half the total emissions from all fossil fuel consumed worldwide during the past 250 years.



Building these coal plants would dramatically increase the chances of catastrophic climate change. What we need to build is carbon-free power. A March 2003 analysis in *Science* magazine by Ken Caldeira et al concluded that if our climate's sensitivity to greenhouse gas emissions is in the mid-range of current estimates, "stabilization at 4° C warming would require installation of 410 megawatts of carbon emissions-free energy capacity each day" for 50 years. Yet current projections for the next 30 years are that we will build just 80 megawatts per day.

Since planetary warming accelerates over time, and since temperatures over the continental US land mass are projected to rise faster than the average temperature of the planet, a warming of 4° C (over 7° F) means that by mid-century, the U.S. temperature could well be rising as much *per decade* as it rose all last century: one degree Fahrenheit. This scenario, which I am labeling "The Global Warming Century," would be a climate catastrophe—one that the American public is wholly unprepared for.

In February 2003, British Prime Minister endorsed the conclusion of Britain's Royal Commission on Environmental Pollution: "to stop further damage to the climate … a 60% reduction [in global emissions] by 2050 was essential."

Unfortunately, the path set by the current energy policy of the U.S. and developing world will dramatically *increase* emissions over the next few decades, which will force sharper and more painful reductions in the future when we finally do act. Global CO_2 emissions are projected to rise more than 50% by 2030. From 2001 to 2025, the U. S. Energy Information Administration (EIA) projects a

40% increase in U.S. coal consumption for electricity generation. And the U.S. transportation sector is projected to generate nearly half of the 40% rise in U.S. CO_2 emissions forecast for 2025, which again is long before hydrogen-powered cars could have a positive impact on greenhouse gas emissions

Two points are clear. First, we cannot wait for hydrogen cars to address global warming. Second, we should not pursue a strategy to reduce greenhouse gas emissions in the transportation sector that would undermine efforts to reduce greenhouse gas emissions in the electric generation sector. Yet that is precisely what a hydrogen-car strategy would do for the next few decades.

HYDROGEN CARS AND GLOBAL WARMING

For near-term deployment, hydrogen would almost certainly be produced from fossil fuels. Yet running a fuel-cell car on such hydrogen in 2020 would offer no significant life-cycle greenhouse gas advantage over the 2004 Prius running on gasoline.

Further, fuel cell vehicles are likely to be much more expensive than other vehicles, and their fuel is likely to be more expensive (and the infrastructure will probably cost hundreds of billions of dollars). While hybrids and clean diesels may cost more than current vehicles, at least when first introduced, their greater efficiency means that, unlike fuel cell vehicles, they will pay for most if not all of that extra upfront cost over the lifetime of the vehicle. A June 2003 analysis in *Science* magazine by David Keith and Alex Farrell put the cost of CO_2 avoided by fuel cells running on zero-carbon hydrogen at more than $250 per ton even with a very optimistic fuel cell cost. An advanced internal combustion engine could reduce CO_2 for far less and possibly for a net savings because of the reduced fuel bill.

Probably the biggest analytical mistake made in most hydrogen studies—including the recent National Academy report—is failing to consider whether the fuels that might be used to make hydrogen (such as natural gas or renewables) could be better used simply to make electricity. For example, the life-cycle or “well-to-wheels” efficiency of a hydrogen car running on gas-derived hydrogen is likely to be under 30% for the next two decades. The efficiency of gas-fired power plants is already 55% (and likely to be 60% or higher in 2020). Cogeneration of electricity and heat using natural gas is over 80% efficient. And by displacing coal, the natural gas would be displacing a fuel that has much higher carbon emissions per unit energy than gasoline. For these reasons, natural gas is far more cost-effectively used to reduce CO_2 emissions in electric generation than it is in transportation.

The same is true for renewable energy. A megawatt-hour of electricity from renewables like wind power, if used to manufacture hydrogen for use in a future fuel-cell vehicle, would save slightly under 500 pounds of carbon dioxide compared to the best *current* hybrids. That is less than the savings from using the same amount of renewable electricity to displace a future natural gas plant (800 pounds), and far less than the savings from displacing coal power (2200 pounds).

As the June 2003 *Science* analysis concluded: “Until CO_2 emissions from electricity generation are virtually eliminated, it will be far more cost-effective to use new CO_2-neutral electricity (such as wind) to reduce emissions by substituting for fossil-electric generation than to use the new electricity to make hydrogen.” Barring a drastic change in U.S. energy policy, our electric grid will not be close to CO_2-free until well past 2030.

A 2004 analysis by Jae Edmonds et al. of Pacific Northwest National Laboratory concluded in that even “in the advanced technology case with a carbon constraint … hydrogen doesn’t penetrate the transportation sector in a major way until *after 2035*.”

CONCLUSION

Hydrogen and fuel-cell vehicles should be viewed as post-2030 technologies. In September 2003, a DOE panel on *Basic Research Needs for the Hydrogen Economy* concluded the gaps between current hydrogen technologies and what is required by the marketplace “cannot be bridged by incremental advances of the present state of the art,” but instead require "revolutionary conceptual breakthroughs.” In sum, “the only hope of narrowing the gap significantly is a comprehensive, long-range program of innovative, high risk/high payoff basic research.” The National Academy came to a similar conclusion.

The DOE should focus its hydrogen R&D budget on exploratory, breakthrough research. Given that there are few potential zero-carbon replacements for oil, the DOE is not spending too much on hydrogen R&D. But given our urgent need for reducing greenhouse gas emissions with clean energy, DOE *is* spending far too little on energy efficiency and renewable energy. If DOE’s overall clean energy budget is not increased, however, then it would be bad policy to continue shifting money away from efficiency and renewables toward hydrogen. Any incremental money given to DOE should probably be focused on deploying the cost-effective technologies we have today, to buy us more time for some of the breakthrough research to succeed.

The National Academy panel wrote that “it seems likely that, in the next 10 to 30 years, hydrogen produced in distributed rather than centralized facilities will dominate,” and so they recommended increased funding for improving small-scale natural gas reformers and water electrolysis systems. Yet any significant shift toward cars running on distributed hydrogen from natural gas or grid electrolysis would undermine efforts to fight global warming. DOE should not devote any R&D to these technologies. In hydrogen production, DOE should be focused solely on finding a low-cost, zero-carbon source, which will almost certainly be centralized. That probably means we won’t begin the hydrogen transition until after 2030 because of the logistical and cost problems associated with a massive hydrogen delivery infrastructure.

But we shouldn't be rushing to deploy hydrogen cars in the next two decades anyway, since not only are several R&D breakthroughs required, we also need a revolution in clean energy that dramatically accelerates the penetration rates of new CO_2-neutral electricity. Hydrogen cars might find limited value replacing diesel engines (for example in buses) in very polluted cities before 2030, but they are unlikely to achieve mass-market commercialization by then. That is why I conclude neither government policy nor business investment should be based on the belief that hydrogen cars will have meaningful commercial success in the near- or medium-term.

The longer we wait to deploy existing clean energy technologies, and the more inefficient, carbon-emitting infrastructure that we lock into place, the more expensive and the more onerous will be the burden on all segments of society when we finally do act. If we fail to act *now* to reduce greenhouse gas emissions—especially if fail to act because we have bought into the hype about hydrogen's near-term prospects—future generations will condemn us because *we* did not act when we had the facts to guide us, and *they* will most likely be living in a world with a much hotter and harsher climate than ours, one that has undergone an irreversible change for the worse.