PANEL ON PUBLIC AFFAIRS

March 2004

THE HYDROGEN INITIATIVE

Current technology is promising but not competitive. More emphasis needed on solving fundamental science problems.

Issue

President Bush has proposed a $1.2 billion Hydrogen Initiative that has a goal of developing a hydrogen-fueled car and supporting infrastructure by the year 2020.

Recommendations

Major scientific breakthroughs are required for the Hydrogen Initiative to succeed. Basic science must have greater emphasis both in planning and in the research program. The Hydrogen Technical Advisory Committee should include members who are deeply familiar with the core basic science problems. "Bridge" technologies should be given greater attention. And, the Hydrogen Initiative should not displace research into promising energy efficiency and renewable energy areas.

Detailed Recommendations: p11, 14

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Executive Summary

In 2003, President Bush announced a multi-year $1.2 billion Hydrogen Initiative intended to reduce the nation's dependence on foreign oil through the production of hydrogen fuel and a hydrogen-fueled car. The Initiative has envisioned the competitive use of hydrogen in commercial transportation by the year 2020.

Currently, the US hydrogen industry produces 9,000,000 tons of hydrogen per year. Several hydrogen-fueling stations are scheduled to open this year. And, several models of hydrogen-fueled cars have been demonstrated.

However, none of the current technologies are competitive options for the consumer. The most promising hydrogen-engine technologies require factors of 10 to 100 improvements in cost or performance in order to be competitive. Further, hydrogen cannot simply be extracted from the air, ground or water – it must be produced. Yet, as the Secretary of Energy has stated, current hydrogen production methods are four times more expensive than gasoline. Finally, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

These are enormous performance gaps. Incremental improvements to existing technologies are not sufficient to close all the gaps. For the Hydrogen Initiative to succeed, major scientific breakthroughs are needed.

Basic science must have greater emphasis both in planning and in the research program. The Hydrogen Technical Advisory Committee should include members of the basic research community who are familiar with the relevant science problems. Further, given the multidisciplinary nature of the scientific problems involved, principal-investigator funded research should be complemented with the creation of several peer-reviewed, competitively bid, Research Centers that focus on the relevant research problems in hydrogen production, storage and use.

In the event that the timeline for hydrogen vehicles slips beyond 2020, there will be greater need for technologies that serve as a so-called "bridge" between the current fossil-fuel economy and any future hydrogen economy. Increasing the focus on basic science and engineering that advances such technologies would serve 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.

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I. Introduction

Technology commercialization projects all face a critical decision point in their development. The capability of the technology must be evaluated, based on the current state of the relevant science, to determine whether the project is ready to proceed aggressively to demonstrations. The Government has faced such decision points before in large-scale commercialization programs.

In his State of the Union Address, the President of the United States proposed an energy-technology program intended to generate the economical production of an alternative fuel that could revolutionize the transportation sector. A diverse group of companies, universities, and national labs would work together. The new fuel would substitute for oil imports and make our country energy independent.

That was 1975: Gerald Ford proposed an initiative for coal-based Synthetic Fuels in his State of the Union Address.[1]

In 2003, President Bush announced a $1.2 billion Hydrogen Initiative intended to generate the economical production of hydrogen fuel as well as a hydrogen car and supporting infrastructure.[2] Like the Synfuel program, the Hydrogen Initiative brings together a diverse group of companies, universities and national labs with an overarching goal of developing a substitute for oil and making our country more energy independent.

Since the Synfuel program goals - and its $2 billion cost - are similar to the Hydrogen Initiative, it is valuable to briefly consider its history.

The falling price of oil in the 80s led to a suspension of industrial support for the Synfuel program and undermined the prospects for commercial application. And, relevant to the Hydrogen Initiative, the Synfuels program had rushed into demonstration projects that were not backed by realistic assessments of the state of technology. As the demonstrations ran into trouble, the program missed an opportunity to advance the state of knowledge and further the long-term commercial prospects of energy production based on clean coal technology. By 1983, the program had lost support in Congress.

In general, the allocation of resources between demonstration projects and relevant basic science must be based on the current commercial readiness of the technology to compete in the market place or to meet national security objectives.

Budgets should be based upon the commercial readiness of the technology.

Demonstration projects play a critical role in a balanced commercialization project. For example, they can lead to cost reductions and accelerate the development of codes and standards. But they can also divert effort toward

[1] January 15, 1975, http://www.geocities.com/americanpresidencynet/1975.htm
[2] January 26, 2003, http://www.geocities.com/americanpresidencynet/2003.htm

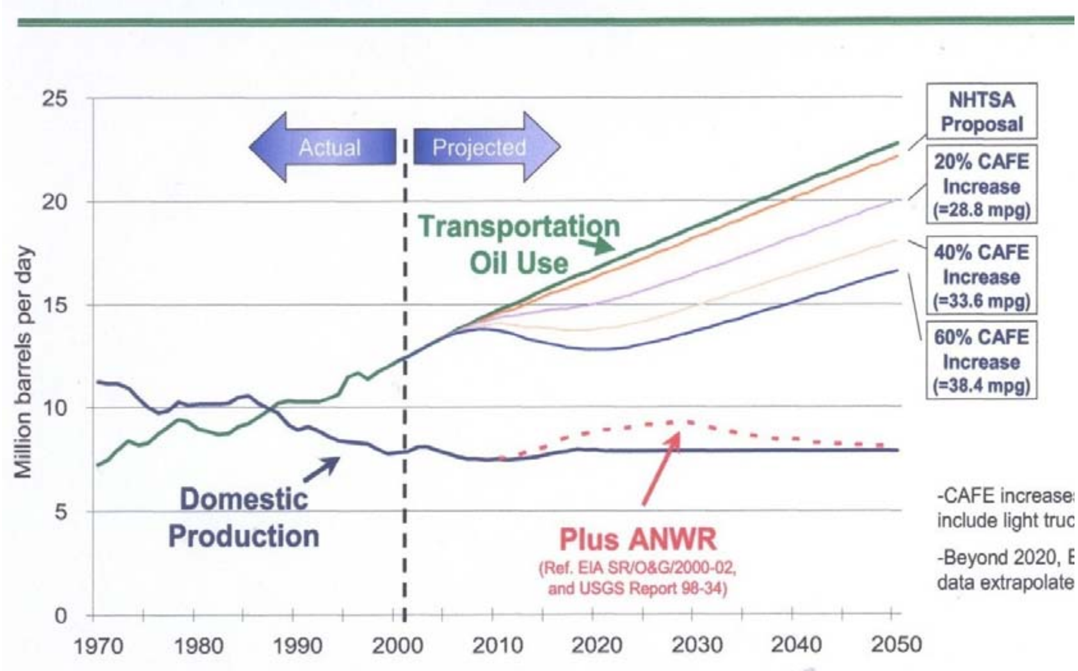
technology with limited potential. So, while demonstrations are an essential part of a government commercialization program, they will only benefit the overall program when a sufficient knowledge base exists.

For the Hydrogen Initiative to be successful, it must give more emphasis to achieving significant advancements in the knowledge base. With such balanced technological development and appropriate long-term perspective, hydrogen has the potential to be economically produced in the future from renewable sources as well as a variety of fossil fuel, including the vast reserves of domestic coal.

If major scientific challenges to storage and use can be overcome, hydrogen fuel also has the potential for addressing the Administration's goal of enhancing energy security by reducing dependence on imported oil. Further, depending on the manner in which the hydrogen fuel is produced, hydrogen fuel can significantly reduce atmospheric release of carbon dioxide.

The Hydrogen Initiative is shaped by the recognition that current US energy dependence is heavily determined by the transportation sector. Transportation accounts for two-thirds of the 20 million barrels of oil the nation uses every day.[3] In order to enhance our energy security, a substitute for oil should be pursued, since neither increasing fuel efficiency nor additional drilling offers a long-term solution to closing the gap between domestic production and oil use (Fig 1).[4]

Figure 1. Projected U.S. Oil Use and Domestic Production



[3] US Department of Energy, http://www.sae.org/calendar/pfs/key_chalk.pdf, p 5.
[4] US Department of Energy, http://www.ccities.doe.gov/conference/palm/pdfs/gross_pathway.pdf, p 4.
This DOE figure is speculative and is based on several long-term projections. It estimates US domestic oil production flat to 2050 at about 2.9 billion barrels per year. However, US production has fallen from a peak in 1970 of roughly 3.5 billion barrels/year to roughly 2.1 billion barrels/year in 2000 (down 40%). Further, the demand lines are based upon long-term projections of economic growth and population increase.

The Initiative has set a goal for "the commercial use of fuels cells in transportation, portable power, and stationary and distributed power applications by 2012."[5] In particular, the Initiative envisions the competitive use of hydrogen in commercial transportation by the year 2020. These 2012 and 2020 goals pose significant challenges. The fundamental problem is that a large performance gap exists between the current state of the technology and the final goals.[6,7,8,9]

None of the existing technologies are a competitive choice for the consumer. The most promising hydrogen-engine technologies require factors of 10 to 100 improvements in cost or performance in order to be competitive. Current production methods are four times more expensive than gasoline. And, no material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed.

Current hydrogen technologies are not a competitive choice for the consumer.

Given these enormous performance gaps, the strategy of devoting too large a share of the program to demonstrations of the automotive application is problematic. To insure the ultimate success of the Hydrogen Initiative, indeed for any new technology, it is critical that resources are properly allocated between demonstration projects and research & development.

The program needs substantially greater emphasis on solving the fundamental science problems. Section 2 of this report examines this issue and makes recommendations to increase the possibility of achieving the 2020 goal of commercial hydrogen transportation.

Because of the large performance gaps, it is possible that the 2020 timeline for hydrogen vehicles may slip. Therefore, it is prudent to maintain strong research programs into technologies that serve as bridges between the current fossil-fuel economy and any future hydrogen economy. Further, technologies that are important complements to the goals of a hydrogen economy should not have their budgets pressed as greater emphasis is placed on the Hydrogen Initiative. Section 3 of this report examines these issues and makes recommendations to insure that important opportunities to advance the state of knowledge and further our nation's energy security are still maintained while prudently undertaking the Hydrogen Initiative.

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5 National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf, p 3.

6 Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE

7 "Basic Research Needs to Assure a Secure Energy Future," (Feb. 2003), http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf

8 Programmatic Publications, DOE Energy Efficiency and Renewable Energy, Hydrogen Fuel Cell Infrastructure Technology Program, http://www.eere.energy.gov/hydrogenandfuelcells/pubs.html#roadmaps

9 "Basic Research Needs for the Hydrogen Economy," a report from the Basic Energy Sciences Workshop (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf

II. Knowledge Gaps & Key Science Areas

More than 95 years of scientific and engineering expertise has been directed at the development of the automobile and its corresponding infrastructure of 125,000 domestic gas stations and worldwide network of oil wells, refineries, and delivery systems. A result of that century-long process has been the creation of a demanding set of consumer expectations. The Hydrogen Initiative envisions developing a new fuel, a new car, and a corresponding infrastructure that can meet consumer expectations within 12 years. This poses a significant challenge to the scientific and engineering community.

> *The Hydrogen car faces challenging expectations from the consumer.*

There are enormous performance gaps between the current state of hydrogen technology and what is required to achieve a commercially viable hydrogen transportation sector. The scientific challenges exist in the all three of the primary areas of the Hydrogen Initiative: production, storage, and use.

To illustrate the challenges, Figure 2 lists just a few of the performance goals established in the FreedomCar Partnership Plan.[10] The table compares these goals to estimates of the current state-of-the-art in a number of possible technologies. However, the challenges are even greater than the chart indicates: each technology component must achieve several performance goals at once. Many technologies may excel in one area but have poor performance in another. Furthermore, the performance goals in each of these stages - production, storage, use - must be met *simultaneously* before the hydrogen economy will be viable. Thus, the magnitude of the problem is even greater than any one given challenge.

The next three subsections examine in detail the specific research challenges faced in the areas of production, storage, and use. There are some common threads to the research challenges posed by each. All would benefit from research into more effective catalysts - chemicals that speed up certain reactions - and membranes - films that pass one compound while blocking others. Most of these steps require the development of new materials that effectively store hydrogen, operate at high temperatures, and withstand corrosion.

Production

Hydrogen does not exist in accessible quantities on Earth. It cannot simply be extracted from the air, ground or water. Instead, hydrogen must be produced. Consequently, an energy source is required in order to create the hydrogen fuel envisioned in the Hydrogen Initiative.[11]

[10] http://www.eere.energy.gov/vehiclesandfuels/pdfs/program/freedomcar_partnership_plan.pdf. The table is not an exhaustive list of performance targets, but an illustrative one. Goals not shown include, for example, standards for the flow rate of hydrogen through a tank and the number of fill and empty cycles it must tolerate. The table also identifies only a sampling of the key challenges.

[11] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

Figure 2. Benchmarks, Knowledge Gaps, and Key Science Areas

Consumer Benchmark[12]	Hydrogen Technology	Minimum factor of Improvement to be Competitive[13]	Challenges	Key Science Areas
Production: $1.50 per gallon	Natural Gas Reforming Coal Gasification Electrolysis	4 to10	Cost Sequestration of Carbon Dioxide Electrolysis Efficiency	Membranes, Catalysts, Renewable Energy, Bio-Engineering, Sequestration, Electrodes
Storage: 300 miles on a tank, 3 to 5 minutes to fill	Compressed Gas Storage Liquid Storage Solid Storage	2 to 3	Leaks, Embrittlement Energy cost, Evaporation Release of fuel at expected temperatures and pressures	Material Science: a new storage material must be developed
Use: 100,000 miles or 5 year warranty, engine cost roughly $2,000- $5,000	Fuel Cell	10 to 100	Impurities, Durability, Materials cost	Material Science, Membranes, Catalysts, Combinatorial Chemistry

Strategically, the long-term goal of the Hydrogen Initiative is to develop an *efficient*, *economical* and *clean* means of producing hydrogen.[14] To be efficient, the production process should not use excessively more energy to create hydrogen fuel than is derived from burning hydrogen fuel. To be economical, hydrogen fuel should not cost more than current fuels. And, for the fuel to be clean, more

[12] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE; National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf, p 19; "Cost and Efficiency of Automobile Engine Plants," Daniel E. Whitney, et. al., (August, 2001), http://web.mit.edu/ctpid/www/Whitney/morepapers/Engine.pdf

[13] Production costs for coal gasification are calculated to become competitive once proposed plants begin operating at full capacity, http://www.nap.edu/books/0309091632/html/, 5-7; Office of Fossil Energy, http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.shtml; Spencer Abraham, http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE; "Basic Research Needs for the Hydrogen Economy," http://www.sc.doe.gov/bes/hydrogen.pdf.

[14] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

carbon-dioxide (CO_2) and toxins cannot be released in creating and using hydrogen fuel than would have been emitted in burning current fuels.

The United States hydrogen industry currently produces nine million tons of hydrogen per year for a variety of non-transportation uses. The primary means of production is the extraction of hydrogen from natural gas through a process known as "steam reforming". However, steam reforming is operating near theoretical limits and is still several times more expensive than gasoline.[15] Further, making it a clean production method would add significantly to the cost.

There is no currently available competitive and long-term means of *efficiently*, *economically* and *cleanly* producing hydrogen. At a minimum, as Secretary of Energy Spencer Abraham has stated, costs must be cut by a factor of four.[16]

A likely near-term option to economically produce hydrogen is coal gasification. The technology is relatively mature, and costs are calculated to become competitive once proposed plants begin operating at full capacity.[17] Yet, there are still technical issues to address. The hydrogen produced by this method contains contaminants and the fuel must be purified before using it in hydrogen fuel-cell engines. To effectively purify the hydrogen, researchers must develop catalysts that resist poisoning by the contaminants in the coal.[18] Furthermore, materials must be discovered that can withstand high temperatures and corrosion.

Coal gasification can release significant quantities of CO_2. Thus, to create clean hydrogen it is critical to develop technology that will capture and store - or sequester - the CO_2. The $1 billion FutureGen program is directing resources at this problem.[19] Since the sequestration problem is a significant scientific challenge with applications that extend beyond the hydrogen initiative, FutureGen should carefully balance Hydrogen Initiative goals and timelines with the opportunity to significantly advance the knowledge base on the relevant science of sequestration.

Hydrogen can also be produced by using electricity to separate hydrogen out of water. This process, called electrolysis, can be made to work using any source of electricity including hydropower, wind, solar, and nuclear fission. However, electrolysis is at best only 75% efficient. The current cost to produce hydrogen in this manner is primarily driven by the cost of electricity and is roughly 4 to 10 times more expensive than gasoline. One of the major research challenges is to develop a more effective catalyst to facilitate the electrolysis process.

Renewable energy research is a direct benefit to the goals of the Hydrogen Initiative.

[15] Department of Energy, http://fossil.energy.gov/programs/fuels/hydrogen/hydrogen-from-gas.shtml
[16] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE
[17] "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs," National Research Council, February 2004, http://www.nap.edu/books/0309091632/html/
[18] "Basic Research Needs for the Hydrogen Economy," (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf
[19] http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_factsheet.pdf

The cost of electrolysis-production improves directly as power sources - such as wind, solar, and nuclear - become cheaper and more efficient. Therefore, a continued investment in renewable energy is a direct benefit to the overall goals of the Hydrogen Initiative. The $1.1 billion Next Generation Nuclear Plant (NGNP) is intended to demonstrate, among other things, commercial-scale hydrogen production by 2015.[20] Since nuclear power is a critical future energy option, Hydrogen Initiative goals and timetables for NGNP should be carefully balanced with the opportunity to significantly advance nuclear power.

Researchers are also exploring novel but promising production methods. For example, in a process known as photolysis, certain algae produce hydrogen by directly splitting water.[21] These biological systems do not require the expensive metal catalysts that are currently used to produce hydrogen. While this research may not contribute in time for the 2020 goal for commercial hydrogen vehicles, it may stimulate ideas for producing a new low cost catalyst. It has the potential to make a long-term contribution, but science advances are required to make it commercially viable.

Storage

Safely and efficiently storing hydrogen in a car's fuel tank are enormous challenges to achieving the hydrogen economy.[22] Indeed, no material exists today that can be used to construct a hydrogen fuel tank that can meet the consumer benchmarks.[23] A new material must be developed.

Hydrogen storage is the primary scientific challenge… A new material must be developed.

As evident in Figure 2, current hydrogen storage technologies are unable by factors of two or more to meet the consumer benchmarks. The requirement that a vehicle be able to travel 300 miles between refueling is a significant challenge for hydrogen storage. Hydrogen is a diffuse gas and the challenge is to store a sufficient amount of it in a tank. To meet consumer expectations, the tank must be capable of being refueled within 3-5 minutes and it must withstand hundreds of refuelings over a 15-year lifetime.

Current hydrogen systems include pressurized tank storage (for gaseous or liquid hydrogen) and "solid-state storage" (in which hydrogen molecules are either absorbed onto or chemically bound up in the storage medium).

High-pressure, lightweight tanks of adequate strength have been made of carbon-fiber-reinforced materials. But, even at the extremely high pressures attainable by this technology, the energy that can be stored in this type of tank is many times less than a comparable tank of gasoline. Another drawback is that a significant amount of energy must be expended to compress the hydrogen into the tank. The

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[20] http://www.nuclear.gov/infosheets/hydrogenfactmarch2003.pdf
[21] "Basic Research Needs for the Hydrogen Economy," http://www.sc.doe.gov/bes/hydrogen.pdf
[22] "Fuel Cell Vehicles: Race to a New Automotive Future"
http://www.technology.gov/reports/TechPolicy/CD117a-030129.pdf
[23] Jan. 2003, Office of Technology Policy report, *Fuel Cell Vehicles: Race to a New Automotive Future*. [OTP]

over-arching research need is for new materials that are strong, reliable, and low cost.

A tank can hold more hydrogen liquid than hydrogen gas, so long as the liquid is kept extremely cold (-450 Fahrenheit). Still, the energy content is roughly a factor of two below the consumer benchmarks. Several automobile manufacturers are conducting research on liquid storage.[24] But, the challenges include a large energy requirement to liquefy the hydrogen and the loss of hydrogen through evaporation. Research needs include strong, durable and leak-proof materials.

Currently, the most promising technology is "solid-state storage" in which hydrogen molecules are embedded in a material. But finding just the right materials in which to embed hydrogen involves tradeoffs between materials that bind hydrogen tightly enough to store it and materials that readily release hydrogen for use at reasonable temperatures and pressures. To date, the storage of hydrogen by this method is a factor of 3 below the benchmarks.

Use

The basic concept of the hydrogen engine has been known since the invention of the "fuel cell" in 1839 by Sir William Grove. In the 1950s, NASA turned the concept into a practical device to produce power for space vehicles. However, as evident from Figure 2, there are significant barriers to developing an economically competitive hydrogen engine.

In a fuel cell, hydrogen is injected at one terminal and oxygen is injected at another terminal. Between these terminals is an electrolyte, or membrane. The hydrogen is split into two protons and two electrons. The electrons flow through an electric motor that turns the wheels of the car, while the protons flow through the electrolyte to the other terminal and combine with oxygen to generate water.

In order to be competitive, fuel cells require significant advances in catalysis and membrane research. Cost-competitive fuel cells require membranes with: very high permeability and selectivity in gas separations; high conductivity; and, durability at high temperatures and in corrosive operating environments. Meeting these three needs calls for an intensive effort in materials synthesis, characterization, and modeling of specially designed materials including: nanostructures, inorganic films, diffusion membranes, and low-cost, high-conductivity proton conductors.

Since catalytic performance is a key factor for many essential elements of the hydrogen economy (including fuel cell efficiency, storage, and production), there is a critical need for breakthrough research into catalysts.[25] Clearly it is desirable to reduce or eliminate platinum in the fuel cell since this is the primary driver of

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[24] Jerald A. Cole, "Overview of the hydrogen-powered economy – today and beyond," California Hydrogen Business Council, presentation to Association of Energy Engineers, Southern California Chapter, 14 March 2002, http://www.ch2bc.org.

[25] Typical publications include: E. Katz *et al.*, "A biofuel cell with electrochemically switchable and tunable output," *J. Am. Chem. Soc.* ***125,*** 6803 (2003); I.V. Mishakov *et al.,* ``Nanocrystalline MgO as a dehydrohalogenation catalyst,'' *Journal of Catalyi* ***286,*** 40 (2002).

the cost. Several cutting-edge research concepts have the potential to address the problem. Using combinatorial chemistry, different combinations of atoms or molecules can be rapidly "produced" by computer and screened for desired properties. When promising trends are revealed, they can be followed up with detailed laboratory work. This technique has already identified a material, which might be up to 40 times more effective as a catalyst than platinum.[26]

The Hydrogen Initiative has an aggressive schedule for fuel-cell demonstration projects.[27] Given the need for significant breakthroughs in membranes and catalysts to make fuel cells commercially competitive, these demonstration goals must be carefully balanced with opportunities to advance the knowledge base.

Hydrogen Initiative Emphasis

There is an enormous gap between our present capabilities for hydrogen production, storage, and use and those required for a competitive hydrogen economy. As detailed in a Department of Energy workshop report, simple incremental advances in the present state of the art cannot close this gap.[28] The only possibility for narrowing the gap significantly is a program of high-risk/high-payoff basic science that is coupled to applied programs. The objective must not be evolutionary advances but revolutionary breakthroughs in understanding.

Figure 3. Hydrogen Initiative Budget in thousands

	FY '04 Request	FY '04 Final	FY '05 Request
Energy Efficiency & Renewable Energy (Dept of Energy)	$165,482	$147,178	$172,825
Fossil Energy (Dept of Energy)	$11,555	$4,889	$16,000
Nuclear Energy (Dept of Energy)	$4,000	$6,377	$9,000
Dept of Transportation	$674	$555	$832
National Science Foundation	$0.0*	$0.0*	$0.0
Basic Energy Sciences (Office of Science, Dept of Energy)	$0.0*	$0.0*	$29,183
Total	$181,711	$158,999	$227,840

* An additional $7.7 million at the Office of Science and $10.3 million at the NSF were identified as on-going research that contributes to the goals of the Hydrogen Initiative.

Given the large performance gaps, basic science is critical to the ultimate success of the Hydrogen Initiative. Yet, basic science is not receiving appropriate

[26] P. Strasser *et al.,* ``High throughput experimental and theoretical predictive screening of materials-a comparative study of search strategies for new fuel cell anode catalysts,'' *J. Phys. Chem. B* ***107***, 11013 (2003).
[27] DOE plans to demonstrate commercial readiness of fuel cells starting in 2009, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/asilomar2003.pdf, p 7.
[28] "Basic Research Needs for the Hydrogen Economy," (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf

emphasis in the program. As the budget breakdown in Figure 3 shows, in FY'04, the nation's primary basic science agencies - the National Science Foundation and the Office of Science at the Department of Energy – did not receive support from the Hydrogen Initiative.

In addition, earmarks skewed key funding priorities in FY '04. For example, the solicitation "Grand Challenge For Basic And Applied Research In Hydrogen Storage" was intended to fund competitively bid proposals addressing the key issue of hydrogen storage. While $30 million was requested for this funding, as the budget moved through Congress, $28 million was earmarked. In total, roughly $42 million of the FY '04 Hydrogen Initiative was earmarked.

The FY'05 request includes $29 million for basic research in the Office of Science. This is a dramatic improvement over FY'04 budgeting and demonstrates a growing recognition that the Hydrogen Initiative cannot succeed until several relevant science problems are solved.

However, the budget directed toward basic research at NSF and Office of Science, still does not reflect adequate appreciation that the large performance gaps can only be reduced by major scientific breakthroughs. Indeed, the budget emphasizes demonstration projects over basic science. Yet, given the enormous challenges facing hydrogen storage, for example, investments in storage demonstrations would be highly premature and there may be little urgency for demonstrations in some other areas at this time.

For the Hydrogen Initiative to be successful, basic science must have greater emphasis both in planning and in the research program.

Basic research should be represented in key planning activities of the Hydrogen Initiative. The White House Office of Science and Technology Policy has included members of NSF and members of Basic Energy Sciences within DOE in its cross-cutting planning. This should be extended. Representatives of BES should participate in the Hydrogen Policy Group within DOE. And, the newly forming Hydrogen Technical Advisory Committee should include members of the basic research community who are familiar with the key science problems.

The Hydrogen Initiative must give greater emphasis to achieving significant advancements in the knowledge base. Demonstration projects can play a critical role in a balanced commercialization project by achieving cost reductions and accelerating the development of codes and standards. But they can also divert effort toward technology with limited potential. So, while demonstrations are an essential part of a government commercialization program, they only benefit the overall program when a sufficient knowledge base exists.

Demonstrations only benefit the program when an adequate knowledge-base exists.

The Hydrogen Initiative must place greater emphasis on solving the relevant research problems in production, storage and use. The programs to be funded should be selected by a competitive peer-reviewed process. Much of the basic and applied research will cut across conventional academic disciplines, with strong linkages between experimental and theoretical explorations. Some of the knowledge gaps can be addressed by incremental progress in well-established research areas while others will require coupled breakthroughs in the physical sciences, biological sciences, and engineering.

Many of the individual knowledge gaps themselves need multidisciplinary teams to make progress. This may be achieved by complementing principal investigator research with multidisciplinary research centers - as is beginning to occur in Initiative planning and as some Members of Congress are urging.

Since the goal of a competitive hydrogen-transportation sector involves both shorter and longer-term components, it would be desirable to connect the multidisciplinary research centers to related efforts in industry and in DOE laboratories. This could be achieved by exchange of personnel and through coordinated efforts housed in industry and in DOE laboratories.

Earmarking funds will not produce the desired, competitive result. Research centers established by federal initiatives that are considered both successful and exemplary have relied on competition and peer review.[29] Key to their success are: an initial competition for funds, with a strong peer review component in the evaluation of proposals; fixed terms for federal support (five years is customary), with reauthorization contingent on a second, comprehensive review; and a fixed total term for federal support (one reauthorization, or a total of ten years, has generally been adequate to accomplish the initial goals and to position the Center, if successful, to continue with private or philanthropic financial sources).[30]

Recommendations:

- Basic science must have greater emphasis in key planning activities for the Hydrogen Initiative. The Hydrogen Technical Advisory Committee should include members of the basic research community who are familiar with the key science problems.

- Basic science should have greater emphasis in the research program for the Hydrogen Initiative. Principal-Investigator research should be increased. And, PI research should be complemented with 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 and national laboratory participation.

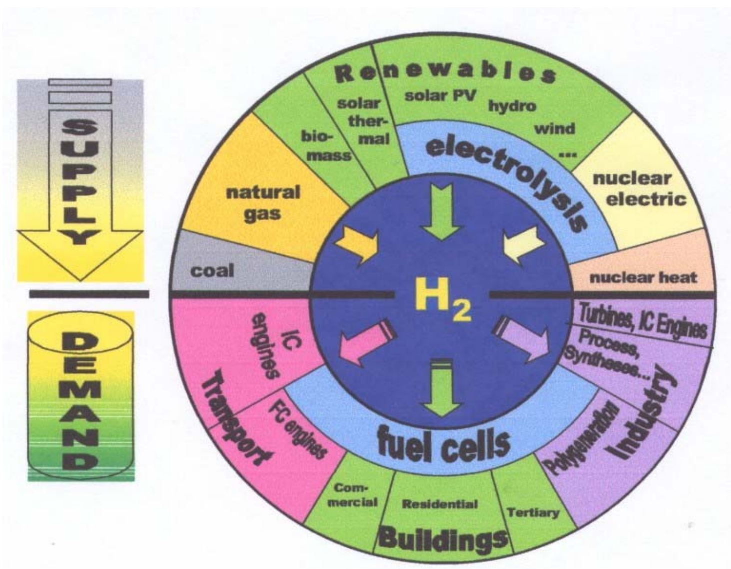
[29] For example, the University-Industry Initiative sponsored by National Science Foundation.
[30] Roger Noll, "Challenges to Research Universities," Brookings Institution (1998).

III. Bridge Technologies & Alternative Applications

The Hydrogen Initiative has envisioned "the commercial use of fuels cells in transportation, portable power, and stationary and distributed power applications by 2012."[31] In particular, the Initiative envisions the competitive use of hydrogen in commercial transportation by the year 2020. These goals pose a significant challenge. The problem is that a large gap exists between the current state of the technology and the final goals.[32]

These challenging timelines should be balanced with a recognition that the development of a Hydrogen Economy can benefit from investing in promising research in a variety of technology areas. Research into energy efficiency, renewable energy, bridge technologies, and hydrogen applications in non-transportation sectors are all investments that present an opportunity to advance the state of knowledge, further commercial prospects that enhance the nation's energy security, and reduce the atmospheric release of carbon dioxide.

Figure 4. Supply and Demand in a Hydrogen Economy [33]



The Federal support of renewable energy and energy efficiency research is appropriately recognized by both the Administration and Congress to be an

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[31] National Hydrogen Energy Roadmap, US Department of Energy, November 2002, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf, p 3.
[32] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association (March 5, 2003), http://energy.gov/engine/content.do?PUBLIC_ID=13384&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE; Programmatic Publications, DOE Energy Efficiency and Renewable Energy, Hydrogen Fuel Cell Infrastructure Technology Program, http://www.eere.energy.gov/hydrogenandfuelcells/pubs.html#roadmaps; "Basic Research Needs to Assure a Secure Energy Future," a report from the Basic Energy Sciences Advisory Committee (Feb. 2003); http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf; "Basic Research Needs for the Hydrogen Economy," a report from the Basic Energy Sciences Workshop (May 2003), http://www.sc.doe.gov/bes/hydrogen.pdf.
[33] European Commission Report "Hydrogen Energy and Fuel Cells". The figure is illustrative and does not represent relative quantities. http://www.ewea.org/documents/12_hlg_summary_vision_report_en.pdf p 3.

essential component of our nation's energy security investment. This investment must also be recognized as an important complement and contributor to the goals of the Hydrogen Initiative. Indeed, hydrogen will require a clean and secure energy source for its production.

It is likely that the early phases of any Hydrogen Economy will rely on production methods that use fossil fuels. As discussed in the Production subsection of this report, the most promising near-term method is natural gas reforming. But, such reforming is operating near theoretical limits and is still several times more expensive than gasoline.[34] However, natural gas reforming is recognized as a viable short-term production method that can be used as a stepping-stone to a Hydrogen Economy. As yet, natural gas reforming is not a clean means of producing hydrogen – carbon dioxide is released in the process. Consequently, limiting overall CO_2 emissions in the early phases of a Hydrogen Economy will come primarily in the form of decreases made through advances in energy efficiency and renewable energy.

As yet, coal gasification is also not a clean means of producing hydrogen. A key research challenge is the capturing and storage – or sequestration – of the CO_2 that is released in the gasification process. The FutureGen program is directing resources at this problem.[35] But again, until an economical solution to the sequestration problem is found, net reductions in overall CO_2 emissions can only come through advances in energy efficiency and renewable energy.

As shown in figure 4, using electricity to separate hydrogen out of water can also produce hydrogen. This electrolysis process can be made to work using any source of electricity including hydropower, wind, solar, and nuclear fission. The current cost to produce hydrogen in this manner is primarily driven by the cost of electricity and is roughly 4 to 10 times more expensive than gasoline. However, the cost of clean electrolysis-production improves directly as power sources - such as wind and solar - become cheaper and more efficient. Therefore, a continued investment in renewable energy is a direct benefit to the goals of the Hydrogen Initiative.

… The Initiative should plan for the possibility that the 2020 timeline may slip.

Since the investments in energy efficiency and renewables benefit the overall goal of energy security and the production goals of the Hydrogen Initiative, the Initiative should not displace research in vital and promising EERE areas.

Some clear planning should be done to address the possibility that the 2020 timeline for commercially viable hydrogen vehicles may slip. In that event, technologies that serve as a so-called "bridge" between the current fossil-fuel economy and any future hydrogen economy will play a bigger role. For example, hybrid gas/electric vehicles are a bridge technology that can "reduce pollution and our dependence on foreign oil until longer-term technologies like hydrogen fuel

[34] Department of Energy, http://fossil.energy.gov/programs/fuels/hydrogen/hydrogen-from-gas.shtml
[35] http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_factsheet.pdf

cells are market-ready."[36] The longer it takes for hydrogen vehicles to become competitive, the more the market will need to rely on such bridge technologies.

Research in "bridge" technologies – such as hybrid gas/electric vehicles or internal combustion hydrogen engines – is on going. Honda and Toyota are marketing hybrid cars. Yet, such technologies can benefit from having appropriate recognition in the overall Hydrogen Initiative. An increased focus in the Hydrogen Initiative on relevant basic science and engineering that advances bridge technologies would serve as a sensible hedge to the possibility that the 2020 goal may slip. It would at the same time maintain the development of technologies that show clear short-term promise.

There are promising short-term applications of hydrogen technology to non-transportation sectors as well. Indeed, as shown in figure 4, transportation is only one of a number of possible applications for hydrogen. The Hydrogen Initiative is primarily focused on meeting goals related to the transportation sector. However, it is worthwhile considering whether applications in other sectors, such as stationary fuel cells, are being given adequate attention in the Initiative. Stationary fuel cells have performance requirements that are considerably easier to meet and have greater commercial readiness.

Promising applications in the non-transportation sector that address the Hydrogen Initiative goal of energy security should be considered as essential parallel investments. Advancing alternative applications – such as stationary fuel cells - that show near-term promise provides a complementary strategy that may help advance the automotive application. Alternative applications would greatly benefit from increased emphasis in the Initiative.

Recommendations:

- Promising Federal investments in energy efficiency research and renewable energy research are an important complement and contributor to the goals of a hydrogen economy and should not be displaced by the growth of the Hydrogen Initiative. These investments become increasingly important in the event that the significant technology hurdles for the Initiative are not met within the proposed timeline.
- There should be increased focus in the Hydrogen Initiative on relevant basic science and engineering that advances bridge technologies such as hybrid vehicles & internal-combustion hydrogen engines.
- Congress should evaluate whether hydrogen applications in the non-transportation sector are receiving appropriate attention within the overall Hydrogen Initiative plan.

[36] Steve Chalk, DOE, November 12, 2003, "Leading our Nation to Energy Independence", http://www.chemistry.org/portal/resources/ACS/ACSContent/government/scproject/chalk.pdf

Appendix I: Methodology, Authors and Review Panel

This report has drawn on the knowledge of a broad range of experts. Together, the authors and reviewers have considerable experience in bench science, the management of industrial technology programs from the laboratory to systems level, management of government R&D programs, and the economics of government energy-commercialization programs. In addition, some authors and reviewers have particular expertise in the areas of hydrogen storage, hydrogen production, and fuel cells.

The authors did not carry out a new analysis of the scientific elements of the Hydrogen Initiative. Instead, the authors distilled the considerable scientific analysis presented in the "Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use" and other sources. Further, the authors had complete access to all the material presented to the National Research Council's Committee on Alternatives and Strategies for Future Hydrogen Production and Use. Finally, the authors examined the Hydrogen Energy Roadmap and numerous presentations by government officials managing the Hydrogen Initiative. All of the background information used in this study is referenced in footnotes throughout the report.

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