Hydrogen Technical Advisory Panel (HTAP)

Analysis of the Effectiveness of the DOE Hydrogen Program

A Report to Congress as Required by the Hydrogen Future Act of 1996 (P.L. 104-271)

December 1998

Foreword

The following Analysis of the Effectiveness of the DOE Hydrogen Program report has been prepared by the Hydrogen Technical Advisory Panel (HTAP). The report was prepared in accordance with the Hydrogen Future Act of 1996 (P.L. 104-271).

Our report indicates that we believe DOE has an active, well-balanced program of core research and development and validation projects, being administered by a team of capable technologists and managers. However, we also indicate that more attention to planning and coordination, as well as increases in personnel and funding are necessary for hydrogen to emerge onto the energy landscape as one solution to the nation's clean energy future.

I appreciate the invaluable advice and assistance of the many people who contributed to the preparation of this report, including the HTAP members, DOE staff, and contract staff.

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HTAP Chairman

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Table of Contents

List of Tables

1.0 Executive Summary

The Hydrogen Technical Advisory Panel (HTAP) was created by the Matsunaga Hydrogen Research, Development and Demonstration Act of 1990 to advise the Secretary of Energy on the implementation and conduct of the DOE Hydrogen Program, and on the economic, technical, and environmental consequences of deploying hydrogen energy systems. The Hydrogen Future Act of 1996 further required that HTAP prepare an analysis of the DOE Hydrogen Program and make recommendations for improvements, including recommendations for additional legislation, to be included in a report to the Congress by the Secretary of Energy.

In this HTAP Report to Congress, the Introduction and Background section discusses the importance of hydrogen to the Nation's energy goals and the status of and challenges to its successful deployment. The Analysis of Hydrogen Program Effectiveness section then discusses the strengths and weaknesses of DOE's Hydrogen Program and makes recommendations for improvements. A Findings section summarizes the recommendations, including recommendations for additional legislation.

1.1 *The Promise and Challenges of Hydrogen Energy*

Hydrogen is an important energy option for the Nation and the world. Based on fossil fuels in the near term and renewable energy sources in the longer term, hydrogen can contribute significantly to each of the five goals stated in DOE's *Comprehensive National Energy Strategy* (April 1998) regarding energy efficiency, energy security, the environment, the expansion of future energy choices, and international competitiveness.

The last two goals alone justify a robust, well-funded hydrogen R&D program. The development of hydrogen technologies for production, storage, distribution, and conversion will provide future generations with a substantial portfolio of clean, secure, and reasonably priced energy options. Hydrogen energy technologies represent a large potential export market that is beginning to emerge. Government-industry collaboration will ensure that US companies with strong hydrogen technology positions will prosper in the international marketplace as worldwide demand continues to grow.

Early in its existence, the Hydrogen Technical Advisory Panel (HTAP) developed a long-term vision for hydrogen energy to serve as a beacon for DOE's Hydrogen R&D Program. The HTAP vision contains two key elements: first, that sometime well into the next century, hydrogen will join electricity as one of the Nation's primary energy carriers; and second, that while most hydrogen will ultimately be produced from renewable energy sources, fossil fuels will provide a long-term transitional resource.

We are still a long way from realizing HTAP's vision for hydrogen energy – but progress is being made, and at an accelerating pace. Fuel cells for distributed stationary power are being commercialized and installed in various locations in the US and worldwide. Transit bus demonstrations are underway in both North America and Europe. And, perhaps most exciting, major automobile companies are now weighing in with major programs to deploy large numbers of fuel cell passenger vehicles within the first decade of the next century. All of these activities involve government-industry collaborations. Furthermore, progress is being made in advancing hydrogen production, storage, and utilization technologies through the efforts of DOE, industry, and hydrogen programs in other countries.

Nevertheless, a number of challenges and barriers remain for widespread implementation of hydrogen energy systems:

- Hydrogen faces the same commercialization barriers as do other new energy technologies, especially renewable energy technologies: undervalued environmental and other societal benefits, continued availability of cheap fossil energy, limited US and other industrialized country demand, and the inability to achieve economies of mass production with low initial demand (i.e., the "chicken and egg" problem).
- Moreover, hydrogen has its own unique set of challenges: continuing high production costs from both fossil and renewable energy sources; lack of attractive, low-cost storage technology; inadequate existing supply infrastructure; lack of widely accepted safety codes and standards; and low visibility among government leaders and the public. In fact, storage and infrastructure issues are pushing stationary and vehicular fuel cell applications toward using very small hydrogen generators for each fuel cell, including placing generators on-board vehicles. This complicates the application and reduces environmental benefits. Finally, many people continue to have a negative perception of hydrogen, relating it to the Hindenburg disaster or the hydrogen bomb.
- We still lack a set of comprehensive and widely shared specific visions for future hydrogen energy systems that will take us to the long-term HTAP vision. Ground transportation and distributed power are but two futures; but even for them, we still don't know how the hydrogen will be produced, transported, or stored. Other futures might include hydrogen's role in carbon sequestration from fossil fuels (including DOE's "Vision 21"), hydrogen-fueled commercial aircraft, and the use of liquid hydrogen as a means of ocean transport of massive quantities of energy (the overarching vision of Japan's WE-NET program).

These challenges and barriers can be addressed in a number of ways:

- By an aggressive RD&D program to bring down production costs from both fossil and renewable energy sources, and to advance hydrogen storage technologies.
- By implementing codes and standards dealing with hydrogen safety, liability, and insurance concerns.
- By enhancing public awareness to emphasize the many positive aspects of hydrogen.
- By means of government incentives and mandates, for hydrogen as well as for other alternative fuels and renewable energy sources, that account for societal benefits and help level the playing field with cheap fossil fuels.

1.2 *Government Organization for Hydrogen RD&D*

Within DOE, formal responsibility for hydrogen energy RD&D resides in the Hydrogen Program within the Office of Utility Technologies under the Office of Energy Efficiency and Renewable Energy (EERE). The Hydrogen Program manages a portfolio of core R&D and validation projects in hydrogen production, storage, and utilization, based on both fossil and renewable energy technologies, that are being conducted at national laboratories, universities, and by industry. Due to its crosscutting nature, other DOE offices within and outside of EERE engage in hydrogen energy-related RD&D activities – including fuel cell work for transportation and power generation in EERE and in the Office of Fossil Energy (FE), biomass conversion in EERE, and basic research in the Office of Energy Research (ER). Compared to the Hydrogen Program's FY 1998 budget of $16 million, expenditures for hydrogen-related RD&D by other DOE offices exceeds $100 million. Outside DOE, Federal agencies such as DOD, NASA, DOT, and Commerce (NIST) engage in hydrogen energy-related RD&D activities – as do state and local governments and other countries.

In addition to carrying out hydrogen RD&D, the Hydrogen Program has two additional key responsibilities: 1) to conduct strategic planning and systems analysis to identify and analyze probable future visions and scenarios for hydrogen energy systems, and 2) to coordinate with all hydrogen energy-related activities in other parts of DOE, at state and local government levels, and internationally – including seeking opportunities for collaboration and for leveraging of Program resources. Associated with the coordination responsibility, are both public and industry outreach efforts. The coordination responsibility alone places a significant management burden on this relatively small program.

1.3 *Analysis of Hydrogen Program Effectiveness*

The Hydrogen Program is generally well managed and executed by a team of dedicated managers and capable and talented technologists. In recent years, the Program has not only experienced growth in the number of core R&D projects in production, storage, and utilization of hydrogen, but is now moving into an expanded effort of validation/demonstration projects. An important element of this growth has been industry participation and cost sharing. The Program has also built strong links with industry through interaction with the National Hydrogen Association and individual companies.

Below we summarize our analysis of the DOE Hydrogen Program under the following headings: Planning and Systems Analysis; Technology Development and Validation; Coordination, Outreach, and Communications; Program Structure (which includes a self-assessment of HTAP's effectiveness); and Funding and Legislation. Major recommendations for improvements are shown in bold print. The report also contains a number of lesser suggestions, only some of which are covered in this Executive Summary.

Planning and Systems Analysis

Recently, program management has made good progress in the development of a strategic plan and in linking that plan to individual RD&D projects by means of their Technology Roadmap and Validation plans. However, a complete roadmap that flows down from HTAP's long-term vision to the individual projects – thereby providing clear rationale for those projects – has yet to be developed. The missing link, as discussed above under Challenges and Barriers, is specific visions and scenarios that tie the long-term vision to the strategic plan. Such visions are needed to fully define collaboration opportunities with other DOE offices and Federal, state, and international entities, and to develop attractive, compelling visions of a hydrogen energy future that government leaders and the public can buy into.

HTAP recommends that DOE conduct vision setting/scenario identification efforts (which may include workshops) to define potential near- and long-term roles and markets for hydrogen energy. Once identified, the Hydrogen Program can utilize its impressive systems analysis capabilities to analyze the various scenarios.

Technology Development and Validation

The report suggests several guidelines for the selection and cancellation of RD&D projects to help manage the large number of hydrogen production, storage, and utilization technologies; the substantial efforts by other DOE offices in hydrogen energy-related technologies; and the high cost of validation/demonstration projects. For example, HTAP recommends that validation projects addressing near-term niche markets be cost shared by the private sector (as is being done) and have a high probability of leading to commercial products.

HTAP commends the Hydrogen Program for aligning its goals for niche markets in transportation and distributed power with those of the National Hydrogen Association's Commercialization Plan (which were developed by industry).

Program balance within the Hydrogen Program's portfolio of RD&D projects is an important strategic issue that has polarized the hydrogen community. While one position favors an emphasis on long-term, renewable-based technologies whose potential markets remain well in the future, another favors nearer-term, largely fossil-based technologies with near-term niche market potential and significant industry involvement. While HTAP recognizes the complexity of reconciling these views, it supports DOE in its current pursuit of both avenues. The growth in Hydrogen Program RD&D budgets, along with industry cost sharing, now provide sufficient resources for this two-pronged strategy.

In addition to the generic issues of project selection guidelines and Hydrogen Program balance, HTAP expresses its support for a number of key technology areas, including: 1) direct hydrogen production from sunlight and water using photobiological and photoelectrochemical technologies, 2) advanced storage technologies, 3) reversible fuel cells, 4) direct hydrogen fuel cell vehicles (i.e., hydrogen stored rather than generated on-board), and 5) hydrogen safety.

Coordination, Outreach, and Communications

Effective coordination with the various entities involved in hydrogen-related development activities can pay handsome dividends in the form of information exchange, technology transfer, project collaboration, leveraging Hydrogen Program funds, and avoiding redundancies in RD&D. Moreover, no single R&D program or DOE office can by itself achieve the long-term vision for hydrogen energy. It requires the concerted effort of multiple entities in both government and industry. Yet, the Hydrogen Program presently lacks sufficient management capacity for carrying out effective coordination. **Thus, HTAP recommends that DOE create a full-time, senior position to coordinate hydrogen-related activities within and outside of DOE.** The Panel further suggests that having it report in at an organizational level higher than the Hydrogen Program might enhance the position's effectiveness.

HTAP commends the Hydrogen Program for its excellent outreach work in overseeing ongoing collaboration to develop codes and standards for hydrogen safety among DOE, the National Hydrogen Association, the International Standard Organization, and the Canadian Government. The Panel encourages DOE to reinvigorate other public and industry outreach activities and considers the recent development of a new outreach plan to be a good start.

Program Structure (including HTAP's performance)

In addition to creating a new position for coordination, HTAP recommends that the Hydrogen Program's previous management structure of having part-time task leaders – drawn from national laboratories and contractor organizations – be restored in some fashion. Otherwise the management burden will continue to be excessive, particularly as the Program continues to grow. Individual assignments for such part-time positions need to avoid conflicts of interest with RD&D project participation.

Even though its purview over hydrogen energy matters officially extends to all of DOE, HTAP recognizes that it has focused the great bulk of its attention on the formal Hydrogen Program (the Office of Transportation Technologies is an exception). The Panel intends to develop future meeting agendas to include more reports and discussion on hydrogen-related activities in other DOE offices (FE and ER, in particular). Moreover, the recommended new coordination position should provide HTAP with additional information on activities beyond the Hydrogen Program.

Funding and Legislation

The report deals with funding on two levels: the Hydrogen Program/DOE level and the Congressional level. At the first level, HTAP encourages Hydrogen Program management to minimize – to the extent it can – RD&D project start/stops resulting from funding discontinuities, a practice that has hurt morale among principal investigators. The Panel also encourages greater disclosure of Program expenditures to HTAP and peer reviewers. HTAP also urges senior DOE management to reduce crosscutting allocations to cover management and administrative costs that the Panel feels have been excessive in recent years.

At the Congressional level, in the short term, HTAP suggests that Congress discontinue its current mandate of one-year funding and consider multi-year funding to increase research productivity. The Panel also discourages the earmarking of funds for large hydrogen energy projects based on decisions that bypass competitive selection, peer review, and HTAP advice.

In the longer term, HTAP believes the goal of utilizing significant amounts of renewable hydrogen energy in the transportation and electricity supply markets in 20-30 years cannot be achieved at or near current modest funding levels. Realistically, however, the Panel recognizes that funding for current Hydrogen Program goals and plans over the next 3-5 years can be supported at the funding levels authorized by the Hydrogen Future Act. **Thus, HTAP urges Congress and DOE to fund the Hydrogen Program at the level authorized by the Hydrogen Future Act. The Panel further recommends an extension of the Hydrogen Future Act, beyond 2001, for five additional years with yearly funding increases comparable to the current Act.**

HTAP also encourages Congress to emphasize hydrogen in new legislation on mandates and incentives for alternative fuels – including giving hydrogen additional consideration over other alternative fuels commensurate with hydrogen's greater environmental and other societal benefits.

In the longer term, it will likely require major R&D funding increases for hydrogen (and renewable energy as a whole) to ensure a secure, sustainable, and environmentally sound energy future for the Nation. It is hoped that well-developed, widely shared visions of such a future will clearly point the way to needed funding increases – before an energy or environmental crisis does. HTAP will continue to work with DOE to develop such visions for hydrogen that could lead to more aggressive funding recommendations by HTAP in the future.

2.0 Introduction and Background

This HTAP Report to Congress was prepared in response to the requirement in the Hydrogen Future Act to "prepare an analysis of the effectiveness of the DOE Hydrogen Program and make recommendations for improvements." The analysis and findings of this report were developed through a comprehensive effort by all current and recent past HTAP members. The results of this effort are presented in the following sections:

- The first section of this Report to Congress provides background information on Federal hydrogen activities, hydrogen's importance in relation to the Nation's energy goals, hydrogen use (past, present, and future), and challenges and barriers to increasing hydrogen energy use. The section begins with a brief discussion of the mandate that created HTAP, Panel membership, and HTAP activities and key contributions to date.
- The second section, Analysis of Hydrogen Program Effectiveness, follows the general structure of the DOE Hydrogen Program with subsections on Planning and Systems Analysis; Technology Development and Validation; and Coordination, Outreach, and Communication. Additional subsections deal with Program Structure and Funding and Legislation.
- The final section summarizes the key findings developed within the Effectiveness section.

2.1 *HTAP Legislative Mandate*

HTAP was created in 1992 in accordance with Section 108 of the Spark M. Matsunaga Hydrogen Research, Development and Demonstration Act of 1990 (P.L. 101-566). The Panel's primary functions are to advise the Secretary of Energy on the implementation and conduct of the US DOE Hydrogen Program and to review and make recommendations on the economic, technical, and environmental consequences of deploying hydrogen energy systems.

The Matsunaga Act was later amended by the Hydrogen Future Act of 1996 (P.L. 104-271) which authorized additional spending on the research, development, and demonstration of hydrogen production, storage, transport, and use. In addition, this Act requires HTAP to prepare an analysis of DOE Hydrogen Program effectiveness and make recommendations for improvements, including recommendations for future legislation.

At the initial Panel meeting in February 1992, the DOE Assistant Secretary for Energy Efficiency and Renewable Energy (EERE) charged HTAP with overseeing hydrogen energy activities throughout the Department. Thus, while HTAP's primary interaction is with the Hydrogen Program in EERE's Office of

Utility Technologies, its purview extends to hydrogen research in other DOE offices. This includes fuel cell activities within EERE's Offices of Transportation and Building Technologies (OTT and OBT) and in the Office of Fossil Energy (FE), and other hydrogen energy-related activities in EERE, FE, and the Office of Energy Research (ER).

HTAP Membership

The Panel is appointed by the Secretary of Energy and has broad representation from industrial, university, environmental, government, and other organizations. Appendix A lists the names and affiliations of members that have served on HTAP. While some members are a part of the hydrogen community, others represent fossil energy, industrial gases, and transportation – areas affected by the development and deployment of hydrogen energy systems. This mix provides the Panel with a balanced perspective while allowing viewpoint diversity. Since HTAP members serve on a pro-bono basis, their time is limited to broad program overview (as has been done in this report) rather than comprehensive planning and project/technology reviews.

HTAP Activities

Through the spring of 1998, HTAP has held 13 two-day, semi-annual meetings that are open to the public. Agendas include, but are not limited to, reports from DOE Program managers and presentations from other Federal representatives, industry stakeholders, and foreign hydrogen program representatives. These meetings have proven to be valuable venues for open discussion of hydrogen energy topics.

Early in its existence, HTAP spearheaded development of a long-term vision of a hydrogen energy future (see text box below) which helped set the broad strategic framework for the guidance it provides to DOE. HTAP has also formed a number of subcommittees to address specific issues identified at the semi-annual meetings, including subcommittees on prioritizing R&D, surface transportation, hydrogen-fueled aircraft, market applications for hydrogen-fueled vehicles, demonstrations, and R&D centers of excellence. Many of the subcommittees have included invited experts from outside the Panel.

US DOE Hydrogen Technical Advisory Panel Vision Statement

Hydrogen will join electricity in the 21st century as the primary energy carriers in the Nation's sustainable energy future. Both energy carriers will ultimately come from renewable energy sources, although fossil fuels will provide a long-term transitional resource. Future hydrogen suppliers will deliver a significant portion of America's energy for transportation and other applications. For these applications hydrogen offers a non-polluting, inexhaustible, efficient and potentially cost-effective energy system derived entirely from domestic energy resources.

HTAP's "*Green Hydrogen Report,*" published in 1995, incorporated the findings and recommendations of the first three HTAP subcommittees on research priorities, surface transportation, and hydrogen-fueled aircraft. The report stressed the importance of hydrogen in the Nation's energy future and proposed a 20-year budget for core R&D projects and cost-shared demonstrations. The report has been widely disseminated and used as a basis for high-level discussions between HTAP leadership and DOE management and Congress.

HTAP's Contributions to Date

Over the past 6 years HTAP has actively contributed to the promotion of hydrogen energy within the DOE Hydrogen Program and in the hydrogen community in general. The contributions listed in Table 1 below are due, at least in part, to HTAP activities. A timeline illustrating HTAP's major activities is located in Appendix B.

Table 1. Examples of HTAP Contributions

Consensus within DOE on the future of hydrogen energy. HTAP's debate to develop its vision helped to achieve the strategic understandings that electricity and hydrogen are companion energy carriers and that hydrogen production from fossil fuels will provide a long-term transition to hydrogen production from renewable energy.
Extensive use of analytical studies. HTAP has encouraged extensive use of analytical studies by the Hydrogen Program. These studies are an inexpensive means to identify energy-significant, economically attractive technologies and pathways for hydrogen while avoiding unnecessary expenditures on technologies and pathways that are not promising.
Improved understanding of the commercial readiness of hydrogen-fueled vehicles. The HTAP market applications subcommittee identified key attributes necessary for successful commercialization of hydrogen-fueled vehicles for both the high-volume, light-duty market and for a variety of small-volume niche markets.
Introduction of the hydrogen corridor concept. The hydrogen corridor concept, promoted by the HTAP demonstration subcommittee, is now a technology validation activity within the Hydrogen Program.
Creation of hydrogen centers. Acting on suggestions from HTAP members and others, an HTAP center subcommittee recommended that DOE form hydrogen centers for both basic and applied research. DOE established university centers in Hawaii and Florida in June 1997.

2.2 *The DOE Hydrogen Program and Activities within DOE and Other Federal Agencies*

The following subsections briefly describe the various hydrogen activities being undertaken by the Hydrogen Program and other DOE offices and Federal agencies.

The US DOE Hydrogen Program

The Hydrogen Program is under the Office of Utility Technologies (OUT) within EERE. The Program conducts research and engineering development in the areas of hydrogen production, storage, and utilization for the purpose of making hydrogen a cost-effective energy carrier for utility, building, and transportation applications. This is accomplished by performing research that introduces renewable-based options to produce hydrogen and decreases the cost of producing hydrogen from natural gas; developing hydrogen-based electricity storage and generation systems that enhance the use of distributed, renewable-based utility systems; demonstrating fueling systems for hydrogen vehicles in urban non-attainment areas; developing and lowering the cost of technologies to produce hydrogen directly from sunlight and water; and supporting the introduction of safe and dependable hydrogen-based energy systems, including the development of codes and standards for hydrogen technologies.

The Hydrogen Program also plays key roles in the analysis of potential hydrogen markets; the coordination of hydrogen energy activities within DOE and between DOE and other Federal agencies, state and local authorities, and foreign governments; and outreach to industry and the public. The identification and evaluation of key market segments and market entry conditions for hydrogen utilization in transportation and electricity generation are important elements of the analysis work. The Program's coordination responsibility helps overcome government compartmentalization and seeks out synergies among the government's various hydrogen activities. The Program's outreach focuses primarily on the development of informed constituencies in the industrial and public sectors as part of the strategy to accelerate the commercialization of hydrogen technologies.

DOE, and particularly EERE and the Hydrogen Program, frequently uses the talent of the ten DOE national laboratories for day-to-day project management in addition to their expertise as world class researchers. Within the Hydrogen Program, project management assignments have been made to the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory. Technical expertise is utilized at these two laboratories as well as at the Jet Propulsion Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Oak Ridge National Laboratory. In addition, the DOE Golden and Nevada Field Offices assist in the management and administration of the Hydrogen Program. Also, university-led hydrogen centers-of-excellence have been established at the Florida Solar Energy Center, University of Miami, and at the University of Hawaii.

The Federal government also participates in the International Energy Agency (IEA) which contributes to the advancement of DOE hydrogen research through international cooperative efforts. Such efforts have included development of system models to support hydrogen demonstration and validation activities, and research in metal hydrides with improved hydrogen storage capacity.

Other DOE and Federal Hydrogen-Related Activities

Activities related to hydrogen are widely conducted throughout the DOE and other Federal agencies. The DOE Hydrogen Program represents only $16 million compared to over $100 million of related hydrogen research within all of DOE. Table 2 summarizes a variety of hydrogen-related activities by DOE offices and Federal agencies, but is by no means a complete list.

Within EERE, the OUT Biomass Power Program conducts R&D for biomass gasification for electricity production, which is germane to hydrogen production. Also, OTT and OBT support the development of fuel cells for transportation and building applications, respectively. In a cost-shared program with industry, both Offices are working on the development of proton exchange membrane (PEM) fuel cell systems for their respective markets.

The current FE strategic plan includes "Vision 21," a concept for clean, efficient energy complexes that utilize coal or natural gas to produce a variety of fossil energy-based commodities including electricity and clean fuels, with the sequestration of by-product CO_2. Hydrogen is a key co-product in a Vision 21 complex and can be used for fuel cells or for a coal-to-liquids conversion process, and possibly as a transportation fuel. ER supports basic research including understanding the mechanisms of chemical, photochemical, electrochemical, and biological reactions that involve hydrogen either directly or indirectly. This strong fundamental knowledge base can be used as the foundation for applied hydrogen programs in other DOE offices and Federal agencies.

The Challenge of Coordinating Hydrogen Activities

The crosscutting nature of hydrogen, coupled with the mission-specific nature of government research in various agencies (including DOE), fosters compartmentalization and makes coordination efforts difficult within DOE and between DOE and other Federal agencies. This difficulty was highlighted in the President's Committee of Advisors on Science and Technology (PCAST) report. The challenge remains to integrate these efforts into a coordinated whole to maximize use and leverage of available resources.

Table 2. Other Federal Activities in Hydrogen

Agency	Office and/or Program	Key Activities	Summary
DOE	EERE OUT – Biomass Power Program	Biomass gasification technologies	Biomass gasification R&D – germane to hydrogen production, including small systems
	OTT – Office of Advanced Automotive Technology	Fuel cells	Fuel cell development for transportation applications; both on- and off-board systems
	OTT – Regional Biomass Program	Anaerobic digestion	Anaerobic digestion produces methane and landfill gases, precursors to hydrogen production
	OBT – Fuel Cells for Buildings Program	Fuel cells	Fuel cell development for building applications
	Office of Industrial Technologies (OIT) – Chemical Industry of the Future Program	Selective surface flow membranes	Hydrogen recovery via SSF membranes; other activities on materials, separations, sensors, and controls
	FE	Gasification technologies Liquid transportation fuels Fuel cells	Hydrogen is a key co-product in FE's "Vision 21" clean, efficient energy complex which can be used for coal-to-liquids conversion, fuel cells, and as a transportation fuel; FE is also developing fuel cells for electric power and cogeneration applications
	ER	Basic research	Biological, chemical, photochemical, and electrochemical reactions involving hydrogen
NASA		Hydrogen fuel use Leak detection Liquid storage	Significant user of hydrogen as an aerospace fuel; research emphasizes hydrogen leak detection and liquid storage
DARPA		Fuel cells Components/systems	Developing a logistic-fueled fuel cell power plant for mobile electric power applications; direct methanol fuel cell component and system development for replacement of military standard batteries
DOD	Navy	Fuel cells Production/storage research	Manages a significant stationary and portable power fuel cell program for submarine applications; limited hydrogen production and storage research
DOT		Transportation fuel cells	Research and demonstration – with DOE, Los Alamos, and Georgetown University – in the application of fuel cells for transportation
DOC	NIST – Advanced Technology Program	Premium power technologies	Create more efficient systems for producing, storing, and delivering advanced power

Coordination of hydrogen activities is made even more complex because funding requests for hydrogen-related research comes from different appropriations bills. For instance, Vision 21 activities are included in FE's budget request in Energy Conservation within the Interior Appropriations Bill, as is EERE's request for improved efficiency technologies, including hydrogen use in industry, building, and transportation sectors. However, the Hydrogen Program and other renewable hydrogen activities are included in EERE's budget request in Solar and Renewable Energy within the Energy and Water Appropriations Bill. Therefore, political committees with differing viewpoints appropriate funding for hydrogen activities, increasing the challenge to coordinate among the various DOE offices.

2.3 *Hydrogen and the Nation's Energy Goals*

Two recently released documents, one developed by DOE and the other by the President's Committee of Advisors on Science and Technology (PCAST), deal with the Nation's energy future. Both documents suggest that further research on efficient and renewable energy technologies, including hydrogen, can add flexibility to our energy consumption while addressing key energy-related challenges.

The DOE's Comprehensive National Energy Strategy (CNES)

DOE is required to submit a National Energy Policy Plan regularly to Congress to ensure that the framework of the Nation's energy policy is modified to reflect evolving conditions, such as better knowledge of our surroundings, changes in energy markets, and advances in technology. The latest plan – the CNES – was released in April and is based on five common sense goals. Produced from fossil fuels in the near term and renewable energy sources in the longer term, hydrogen can contribute significantly to each of the five goals, as follows:

- **Improve the efficiency of the energy system.** The primary hydrogen utilization device – the fuel cell – is far more efficient than comparable combustion processes for both stationary and vehicular power generation.
- **Ensure against energy disruptions.** Hydrogen can be produced from a variety of domestic fossil and renewable energy sources.
- **Promote energy production and use in ways that respect health and environmental values.** Hydrogen is the cleanest burning of all fuels. Fuel cell vehicles with on-board hydrogen are truly zero emission vehicles. Hydrogen produced from renewable energy sources adds no net carbon dioxide to the environment.
- **Expand future energy choices.** The development of advanced technologies for hydrogen production (both from fossil and renewable energy sources), storage, and utilization (e.g., fuel cells) will substantially enhance the Nation's portfolio of energy technologies. Hydrogen will permit greater

utilization of renewable energy sources for both distributed power generation and transportation. For distributed power, hydrogen production and storage uncouples intermittent renewable energy availability from continuous power demand; for transportation, hydrogen provides the means of converting solar energy into transportation fuel.

- **Cooperate internationally on global issues.** Hydrogen energy technologies can provide developing countries with clean, secure energy options for achieving economic growth. Hydrogen energy technologies represent a large potential export market that is beginning to open up. US companies with strong hydrogen technology positions will prosper in the international marketplace as worldwide demand continues to grow. Hydrogen also offers opportunities for increased international collaboration in research and development.

The President's Committee of Advisors on Science & Technology (PCAST)

PCAST issued a report entitled "*Federal Energy Research & Development for the Challenges of the Twenty-First Century*" (November 1997) in response to a request from President Clinton to review the current national energy R&D portfolio and make recommendations on how to ensure that the US has a program addressing its energy and environmental needs for the next century.

In its report, PCAST proposed a substantial increase in Federal spending for applied energy technology R&D, the largest share going to energy efficiency and renewable energy technologies – a major change in emphasis from the current Federal R&D Program. With this new R&D emphasis, the PCAST report acknowledges and supports long-term opportunities for important advances in a wide range of both hydrogen-producing and hydrogen-using technologies.

2.4 *Hydrogen Energy – Past, Present, and Future*

The following subsections introduce the various uses – past, present, and future – of hydrogen in the Nation's economy.

Past

The Hydrogen Program was initiated following the Arab oil embargo in the early 1970s, peaking after the second embargo in the late 1970s. At that time the Program had more than $30 million (1979 dollars) of appropriated funding. With the moderate energy prices of the 1980s, hydrogen was relegated to a position of very low importance in the Nation's energy priorities. Hydrogen funding ebbed at approximately $2 million in 1986.

Hydrogen as a chemical feedstock (primarily for petrochemical and fertilizer uses) has been a substantial and growing industry throughout the second half of this century. Hydrogen use as a rocket fuel has also grown throughout the 80s and 90s.

Hydrogen energy has experienced a rebirth that was driven by legislation such as the Matsunaga Act, Energy Policy Act, and the Hydrogen Future Act; a focus on sustainable development and concern over global climate change; and technology breakthroughs, especially PEM fuel cells.

Present

Virtually all hydrogen is presently derived from fossil fuels – either directly from stream reforming of natural gas (the dominant production technology) or partial oxidation of other fossil fuels, or indirectly as a by-product of other fossil fuel-based processes such as catalytic reforming of petroleum. The electrolysis of water accounts for only a tiny fraction of hydrogen production.

Currently aerospace represents the only significant use of hydrogen as a fuel – and it amounts to only 0.1% of hydrogen production. The remaining 99.9% is used as a chemical in a variety of industries. Petroleum refining and the production of ammonia and methanol account for approximately 95% of total hydrogen use while other chemicals, pharmaceuticals, food, glass, metals, and electronics account for much of the remainder. Nearly 98% of hydrogen is produced and used at the same location (i.e., on-site production); the remaining 2% is transported to other locations by gaseous pipelines or truck as a cryogenic liquid or compressed gas.

A variety of fuel cell applications utilizing hydrogen, primarily in the vehicle market, are now beginning to emerge but have yet to account for any appreciable hydrogen use.

Future

Hydrogen's long-term potential value lies primarily in serving as a versatile energy carrier whose production will ultimately derive from renewable energy sources and whose consumption at the point of use will occur with little or no pollution and high efficiency. In addition to electricity generation and road vehicle applications, hydrogen has potential as a fuel for airplanes, ships, and locomotives.

Distributed Power. Fuel cells utilized as distributed electric generating systems could significantly reduce the need for new centralized power stations and long transmission lines. Units of the size to power a commercial building are being commercialized. Fuel cells can also be used for off-grid, remote village power where electricity costs are high and current power sources are either unavailable or unreliable. Until an infrastructure is available that can supply hydrogen to distributed power fuel cells, the needed hydrogen will have to be generated at individual fuel cells from fossil fuels, typically by means of dedicated small natural gas reformers.

Utilization of fuel cells for distributed power, on or off the grid, opens up opportunities to utilize renewable power sources – with possible water electrolysis and hydrogen storage – helping to uncouple intermittent renewable energy supply from electric power demand.

Transportation Applications. Vehicles of the future will likely have an electric motor to drive the wheels, with electric power coming from fuel cells. With no moving parts, fuel cells are a silent, nearly maintenance free, and highly efficient means of providing the electric power. Fuel cells convert hydrogen directly into electricity without burning it. However, the direct, on-board utilization of hydrogen requires a lightweight, low-volume storage system that has a high energy density, is reusable or rechargeable, and is safe. Vehicular fuel cells may utilize fuels other than hydrogen, including natural gas, methanol, ethanol, or gasoline, converting them to hydrogen by means of miniature on-board hydrogen generators. Compared to direct hydrogen fueling, on-board generation reduces efficiency and increases emissions, although it still provides substantial improvements over conventional internal combustion engine vehicles. The use of other fuels is likely until the storage technology and infrastructure for hydrogen supply begin to mature.

A number of hydrogen-fueled transit bus demonstrations are currently underway in North America and Europe. Even more noteworthy are recent plans of major automobile manufacturers to develop fuel cell passenger vehicles, especially the Daimler Benz and Ford alliance with Ballard Power Systems – the leading supplier of PEM fuel cells – with a goal of putting 2,000 fuel cell vehicles on the road by 2004 (most likely with on-board methanol reformers).

Hydrogen-fueled commercial aircraft and ships represent other transportation applications that could substantially increase the use of hydrogen. For example, to fuel future aircraft with hydrogen rather than jet fuel, a single major airport would require as much liquid hydrogen as is currently produced in all of North America.

CO_2 Sequestration and Other Visions for Large-Scale Use of Hydrogen Energy. Reforming natural gas to hydrogen and the gasification of coal provide platforms for CO_2 sequestration as embodied in FE's Vision 21. The remaining decarbonized fuel is hydrogen. Should wide-scale CO_2 sequestration be implemented, massive volumes of hydrogen transported by long-distance pipelines could become a reality. Another vision that calls for large-scale generation of hydrogen is the use of hydrogen, most likely in liquid form, as an energy carrier for the ocean transport of energy. The Japanese WE-NET program and the earlier Canadian/European Euro-Quebec Hydro-Hydrogen program are based on this vision.

Transition to Renewable-Based Hydrogen Production. The ultimate goal is to expand the use of hydrogen and produce it from renewable resources – after a transition period of production from fossil fuels such as natural gas. Hydrogen energy has the potential to replace fossil fuels in nearly every sector of the economy. Eventually, the clean and sustainable production of hydrogen will utilize renewable resources, such as biomass, sunlight, wind, hydropower, and others.

2.5 *Challenges and Barriers*

Hydrogen, along with other new, primarily renewable technologies, faces the chicken-and-egg problem of having high costs – therefore being limited to low market volumes – but needing large market volumes to drive costs down.

In the US, extremely low fossil fuel energy costs present a barrier to use of higher cost hydrogen use. One reason for this is that many external factors – including environmental and social costs – are not incorporated into the price of energy. Natural gas has become the fuel of choice because of its low cost, minimal environmental impact, use in advanced turbine technology for power generation, and because of the competitive pressures of electric industry restructuring. This trend to natural gas-fueled power generation is likely to continue since it contributes positively to the Nation's environmental objective, particularly by reducing CO_2 emissions to the extent that gas replaces coal.

Fuel cell technologies are the key to drive further hydrogen utilization; however, costs are still high. Although fuel cells are available and in use for a variety of applications, the question of market readiness remains for both hydrogen-fueled vehicles and stationary power units. The need for compact, efficient means of storing hydrogen for on-board mobile and stationary applications is one market readiness concern, while the lack of an appropriate infrastructure for both hydrogen supply and delivery is another. The attainment of competitive hydrogen energy systems will require additional advances in selected production, storage, and conversion technologies before increased use of hydrogen is truly feasible.

Another key concern is that current public awareness of hydrogen's energy potential is either very limited or negative (e.g., the H-bomb and the Hindenburg).

These challenges and barriers to hydrogen energy can be addressed in a number of ways, including:

- An aggressive R&D Program to bring down both fossil fuel and renewable energy source production costs and to improve hydrogen storage technologies.
- Implementation codes and standards dealing with hydrogen safety, liability, and insurance concerns.
- Enhanced public awareness to emphasize the positive aspects of hydrogen.
- Government incentives and mandates for hydrogen as well as other alternative fuels and renewable energy sources that account for societal benefits and help level the playing field with cheap fossil fuels.

3.0 Analysis of Hydrogen Program Effectiveness

To analyze the effectiveness of the Hydrogen Program, HTAP drew on its six years of exposure to hydrogen energy matters, plus the varied backgrounds and experience of its members. HTAP began by conducting a survey of over 50 individuals in industry, research, and government involved or interested in hydrogen energy (a report of the survey was published in May 1998). Individual HTAP members then submitted comments and suggestions for the initial report draft. An HTAP subcommittee was formed to develop a second draft. The subcommittee also reviewed and commented on the DOE Hydrogen Program's report to Congress prepared by Program management. Subsequent HTAP report drafts resulted from further input from both HTAP members and DOE.

This section follows the general structure of the DOE Hydrogen Program – with subsections on Planning and Systems Analysis; Technology Development and Validation; and Coordination, Outreach, and Communication. Additional subsections deal with Program Structure and Funding and Legislation. The final section of the report summarizes the findings developed in this Effectiveness section.

3.1 *Planning and Systems Analysis*

Planning and systems analysis provide linkages (i.e., roadmaps) between the long-term vision for hydrogen energy, presented in the Introduction and Background section of this report, and the numerous individual RD&D projects within the Hydrogen Program. They also help provide a linkage between the Hydrogen Program and hydrogen-related activities of other organizations both within and outside of DOE. Because planning and systems analysis are cost-effective means of identifying energy-significant, economically attractive technologies and pathways for hydrogen – and of avoiding unnecessary expenditures on unfavorable technologies and pathways – HTAP has placed its highest priority on the Hydrogen Program's planning and systems analysis effort. Planning and systems analysis consist of such activities as:

- Identification and analysis of specific near- and long-term visions and scenarios for hydrogen energy that connect to the HTAP long-term vision presented in the preceding section.
- Development of strategic plans defining goals and strategies to implement the visions and scenarios.
- Development of operating plans that links the goals and strategies to the individual RD&D projects in the Hydrogen Program portfolio.
- Portfolio analysis to match RD&D projects with key market segments and market entry conditions.
- Technical/economic evaluations of individual RD&D projects to gauge their future economic

potential and to help set research performance targets.

The Hydrogen Program has made significant progress in many of the above planning and systems analysis activities. Nevertheless, many in the hydrogen community feel that the Program currently lacks a clear and complete roadmap that starts with the long-term vision and extends down to the Program's portfolio of RD&D projects – thereby providing a rationale for those projects. HTAP agrees. The following comments address the Hydrogen Program's effectiveness in carrying out each of the above listed planning and systems analysis activities.

Scenario Identification and Analysis

The Hydrogen Program has assembled an excellent cadre of analysts from industry and academia to carry out scenario analyses using effective methodologies such as pathway analysis. For example, extensive analysis is being done on both fuel cell vehicles and distributed power. The Program, however, has been less effective in scenario identification – i.e., specific visions and scenarios that flow down from HTAP's overarching vision. While fuel cell vehicles and distributed power are important scenarios, the Program needs to further identify plausible scenarios that hold long-term promise for significant hydrogen energy applications (including relevant scenarios developed in other DOE programs). Examples might include hydrogen from decarbonization of natural gas and coal in connection with carbon sequestration (linked to Fossil Energy's Vision 21); co-production of electricity, chemicals, and hydrogen; hydrogen-fueled commercial aircraft; hydrogen-fueled ships; and hydrogen for ocean energy transport.

Since comprehensive vision/scenario development is a significant need, **HTAP recommends that the Hydrogen Program host vision setting/scenario development exercises, including workshops.** From these scenarios, near- and long-term domestic and foreign markets for hydrogen energy can be defined more thoroughly. Once identified, the Program has the people and tools to analyze the scenarios. Compelling visions and scenarios of a hydrogen energy future, amply supported by favorable systems analyses, will advance the concept of hydrogen energy to senior DOE management, the Congress, and the public.

Strategic Planning

The Hydrogen Program recently published a significant strategic plan, which HTAP reviewed during its development. The plan now needs to be effectively communicated to Program participants and others in the hydrogen community.

Operating Plans

The Program has made a good start in developing plans for technology roadmaps and validation projects which will help link the strategic plan to individual RD&D projects. Additional work is now needed to fully develop and implement these plans. (The term "roadmap" used here by DOE is a small part of the total roadmap discussed above that links vision to projects.)

Portfolio Analysis

HTAP understands that rigorous portfolio analysis is an expensive, time consuming endeavor. Thus, while its value is clear, HTAP hesitates to make a strong recommendation that the Hydrogen Program undertake a full-blown portfolio analysis on its own. Rather, the Panel strongly supports PCAST's recommendation of portfolio analysis for all DOE's energy R&D under a new portfolio manager position. In the absence of this top-down effort by DOE, HTAP does encourage the Hydrogen Program to carry out a modest, if less rigorous, effort in portfolio analysis.

Technical/Economic Evaluations

The Hydrogen Program has established excellent capability for conducting evaluations on individual RD&D projects. HTAP encourages the Hydrogen Program to continue to aggressively utilize this capability to regularly evaluate all applicable RD&D projects in its portfolio, including its use for setting performance targets.

3.2 *Technology Development and Validation*

In this subsection, HTAP offers suggestions on selection criteria for RD&D projects (as well as for choosing to drop projects), states its position on the issue of Program balance (an issue of widely differing opinions in the hydrogen community), suggests some execution criteria for validation/demonstration projects, and comments briefly on certain specific RD&D project areas.

RD&D Project Selection Criteria

General Criteria for all RD&D Projects. A myriad of factors influences the selection of RD&D projects – technical, commercial, organizational, funding, and political. Project selection within the Hydrogen Program is made even more challenging by the complex organizational structure of DOE coupled with the crosscutting nature of hydrogen technologies. While planning and systems analysis helps guide the selection process, further selection criteria are helpful.

HTAP suggests the following criteria:

- Favor projects and technologies that represent essential steps on the path toward achieving hydrogen's future as a major energy carrier.
- Select projects in technologies and applications that are not included in other DOE programs. Key examples are direct hydrogen production from sunlight and water, advanced hydrogen storage technologies, reversible fuel cells, and advanced electrolysis technologies. Direct hydrogen fuel cell vehicles (i.e., hydrogen stored on-board) and the associated refueling infrastructure are perhaps the most important current application technology areas.
- Favor systems and pathways that include hydrogen storage, transportation, and/or distribution steps. Systems that produce hydrogen with technologies under development by other programs (whether from fossil fuels or biomass) which then use the hydrogen in an adjacent device (e.g., to produce power from a fuel cell) are probably not suitable for Hydrogen Program support – unless other considerations exist that strongly support Program goals, such as highly leveraged investments with other programs.
- Favor systems that produce and/or utilize hydrogen from renewable energy sources. Nevertheless, situations exist that call for support of fossil fuel-based technologies, such as:
  - when they can ultimately lead to use of renewable energy
  - when they facilitate early market entry of hydrogen-energy technologies
  - when they are associated with decarbonization/carbon sequestration scenarios and are highly leveraged with Fossil Energy funding
  - when they share component-level technologies in areas, such as hydrogen purification and storage
  - when they can produce hydrogen as a co-product (for energy applications) from multiple product facilities
  - when they involve dual-use technologies, with one use involving hydrogen energy.

The many fossil fuel-, biomass-, and fuel cell-based RD&D activities in DOE and other Federal and state organizations provide the Hydrogen Program with a number of collaborative opportunities. For those shared projects that are mostly non-hydrogen in content, the Panel recommends that the major funding and project management responsibility should not come from the Hydrogen Program. The Program needs to be involved in such projects to the extent of adopting and modifying project work in accordance with Program goals and strategies.

Validation Project Selection Criteria. Given that validation/demonstration projects can become very expensive, very quickly, HTAP offers additional selection criteria. HTAP feels that both technology-push and market-pull are valid rationales for validation projects. To justify a technology-push project the technology needs to have successfully moved through the laboratory phase as far as possible, and should hold promise of opening up future mass markets for hydrogen energy – for example, the cost-effective production of hydrogen from sunlight and water in one step. Market-pull projects aimed at near-term niche markets should be largely cost-shared by the private sector and have a high probability of leading to commercial products.

The Hydrogen Program's current portfolio of validation projects is cost-shared appropriately at 50-50. Its goals for niche markets in both transportation and distributed power are very consistent with those of the National Hydrogen Association's (NHA) Commercialization Plan, for which the Program is commended by HTAP.

Terminating RD&D Projects. In its decisions to cancel projects, the Hydrogen Program typically relies on feedback from the peer review process with regard to achieving technical project objectives. HTAP encourages Program management to also give strong consideration to the alignment of projects with overall Program goals and objectives in reaching these decisions. Multi-year RD&D projects that no longer fit the evolving Program goals are candidates for cancellation, as are projects with near-term, commercial thrusts that fail to attract industry interest. For example, the group of R&D projects on hydrogen ICE hybrid vehicles should have been canceled for precisely these reasons, even though they had high technical merit. A PCAST recommendation was the impetus for the Hydrogen Program to cancel these expensive projects.

Even projects that fit Program goals and continue to show some technical progress can be candidates for cancellation when such projects make only minimal progress at a high cost over a number of years without acceptable expectations of significant ultimate success.

Program Balance

The Hydrogen Program needs to strike a balance between a number of competing elements:

- Core R&D versus validation/demonstration projects.
- Within core R&D, production versus storage versus utilization technology areas.
- Long-term, renewable-based versus short-term, fossil-based technologies.

The recent HTAP survey showed a strong polarization within the hydrogen community with regard to

Program balance. One position favors a focus on near-term market opportunities, necessarily based on hydrogen from fossil fuels, to be pursued through industry-led validation/demonstration projects. The other position prefers to emphasize long-term, renewable-based core R&D with a low priority for validation projects. Advocates of the latter position are concerned that short-term, fossil-based R&D projects and expensive validation projects that do little to advance the technology will siphon scarce resources away from realizing the Program's long-term vision of a sustainable hydrogen energy future.

While HTAP recognizes the complexity of reconciling these views, it supports DOE in its current pursuit of <u>both</u> avenues. Growing Hydrogen Program R&D budgets, with industry interest in cost sharing, provide sufficient resources for a two-pronged strategy. If, however, funding levels were to decline, the Panel firmly believes that core R&D – especially long-term, renewable-based R&D – should not suffer. A strong core R&D effort must be protected to help ensure the realization of the vision as well as to maintain critical capabilities and people at key institutions that support the Hydrogen Program. Effective communication by the Hydrogen Program, showing that both strategies are being rigorously pursued, could help alleviate many concerns.

<u>Validation Project Execution</u>

HTAP recommends the following practices for executing validation/demonstration projects. All validation projects – whether being undertaken for long-term technology development (technology-push), nearer-term niche market penetration (market-pull), or for public awareness – should have:

- A comprehensive safety review. The review should follow established industry practices for safety assessments and process hazards reviews. Affected local authorities (fire marshals, etc.) also need to be involved early on in project planning and execution. DOE must supplement the resources of project teams that lack the necessary safety expertise. At its conclusion, each project should be required to contribute a project safety summary report for inclusion in the *Sourcebook for Hydrogen Applications* being developed under NREL, as well as sending it to the appropriate codes and standards organizations. Safety is critical! The hydrogen energy effort cannot afford a single accident.
- A project scope at the systems level (i.e., demonstrate a total process) – if technology risk and project cost are acceptable. Maximum use of off-the-shelf components for existing technology parts of the process can help minimize risk.
- A public outreach activity. HTAP is generally not in favor of validation/demonstration projects that are conducted solely for the purpose of public awareness – unless a large percent of funding comes from outside the Hydrogen Program. Nevertheless, once a validation project based on

technology-push or market-pull is undertaken, it also affords an opportunity for public outreach – an opportunity that should not be missed. Thus, HTAP recommends that each validation project be required to have a public outreach plan.

In addition to the above requirements, all market-pull projects should have:

- Industry leadership and cost sharing.
- A comprehensive business plan showing high-probability of leading to a commercial product.
- CRADAs or other collaborative mechanisms for national lab participation.

Specific RD&D Project Areas

Although HTAP generally advises DOE at the programmatic level, it is appropriate to also comment on a few key technologies.

Advanced Production, Storage, and Utilization. HTAP strongly supports the Hydrogen Program's ongoing core R&D work in photobiological and photoelectrochemical hydrogen production from sunlight and water and in advanced storage technologies. Technological breakthroughs in any of these "Holy Grails" of hydrogen can lead to large-scale implementation of hydrogen energy systems. The Panel also supports advanced electrolysis and reversible fuel cell R&D since these technologies underlie distributed power scenarios for hydrogen and are not being researched by other DOE programs.

Hydrogen Combustion. While HTAP agrees with the PCAST recommendation that the major R&D effort under the Hydrogen Program for hydrogen hybrid vehicles be terminated, the Panel continues to support some level of continuing combustion R&D, if clearly supported by Program goals. Examples might be hydrogen-fossil fuel blends for combustion engines, combustion-based consumer products for developing-country markets, and hydrogen generator sets for distributed power applications.

Fuel Cell Vehicles. As a result of major industry participation, light-duty fuel cell vehicles appear to be progressing quickly toward the marketplace – but with on-board reforming of methanol or gasoline rather than with on-board hydrogen storage. HTAP disagrees with the OTT position of only supporting industry's preferred on-board reformation option instead of also encouraging the direct hydrogen option based on ground-based reformation and on-board hydrogen storage – an option that provides significantly greater societal benefits. The Panel is concerned, however, that the efforts of the relatively small Hydrogen Program to promote the direct hydrogen option may not be able to make a sufficient impact on its own. **Thus, HTAP encourages DOE and Congress to give additional support to hydrogen in**

Federal alternative-fueled vehicle programs.

Hydrogen Safety. The Hydrogen Program's R&D work in hydrogen safety should continue to receive high priority. Hydrogen safety R&D should be based on the needs identified by codes and standards organizations and independent safety authorities. These might include improved, simplified dispersion analysis; improved detectors and odorants and guidelines for their use; and fire and explosion suppression technologies based specifically on the flammability and explosibility of hydrogen.

Aircraft. HTAP encourages DOE to strengthen its ties with NASA and industry in order to revisit hydrogen-fueled aircraft. Beginning with past NASA-industry studies and ongoing work in Europe, scenarios can be identified and analyzed, and perhaps R&D work recommended, possibly in collaboration with the Europeans.

3.3 *Coordination, Outreach, and Communication*

The Matsunaga Act of 1990 charged DOE with coordinating hydrogen energy activities between DOE and other Federal agencies. DOE, in turn, delegated interagency coordination responsibility to its Hydrogen Program – along with intra-DOE, state, local, and foreign government coordination. Moreover, in recent years, the Hydrogen Program has undertaken the tasks for public and industry outreach. These massive efforts are the responsibility of only a small number of program managers at DOE.

The HTAP survey showed overall dissatisfaction with many aspects of the Hydrogen Program's coordination, communication, and outreach efforts. HTAP tends to agree, but also recognizes the high workload burden posed by these activities. This subsection assesses the Program's coordination and outreach activities (including the development of safety guidelines and codes and standards as a part of outreach). It also addresses communication, especially as it pertains to peer reviews.

Coordination

Federal agencies, including DOD, DOT, NASA, and NIST, have programs that deal either directly or indirectly with hydrogen research. Many states, especially those that have adopted stringent clean air policies such as California, have aggressive programs that deploy clean technologies. Many countries (e.g., Japan, Germany, etc.), as well as international organizations like the International Energy Agency (IEA), have extensive hydrogen programs. Effective coordination with these numerous entities can pay handsome dividends in information exchange, technology transfer, collaboration, leveraging of Program funds, and avoiding redundancies in RD&D. Moreover, no single R&D program or DOE office can, by itself, achieve the long-term vision for hydrogen energy. It will require the concerted efforts of multiple entities in both government and industry.

Good coordination now exists within DOE among the Hydrogen Program and the Offices of Transportation and Buildings Technologies in the area of PEM fuel cells. The Program is also beginning promising coordination initiatives with the Offices of Fossil Energy and Energy Research, as recommended by PCAST, as well as with NASA. DOE senior management should encourage and assist in facilitating these coordination activities.

HTAP is unaware of any significant collaboration between the Hydrogen Program and other Federal agencies. At the state and local level, the Program has a successful project underway in Palm Desert, California and has developed an affiliation with the Nevada Test Site. HTAP feels that with additional resources more can be done between the Program and state and local levels to include, for example, the California South Coast Air Quality Management District, the California Energy Commission, and some state energy offices like New York, Ohio, and Minnesota. At the international level, the Hydrogen Program has been very active in IEA hydrogen R&D activities. However, some respondents of the HTAP survey questioned whether coordination with IEA is yielding results commensurate with the effort. While HTAP generally feels that IEA results have been useful, it encourages DOE to communicate IEA activities and results more widely.

Clearly the challenge of achieving effective coordination is daunting given the ubiquitous nature of hydrogen. PCAST recommended the creation of a manager of crosscutting technologies position to deal with technologies like hydrogen on a DOE-wide basis. HTAP supports that recommendation; it would undoubtedly benefit hydrogen coordination within DOE. However, even if DOE establishes a manager of crosscutting technologies position, the task of effective coordination in hydrogen energy, which extends beyond DOE, will continue to be a major one – one that HTAP believes is beyond the capability of current Hydrogen Program senior management.

Thus, HTAP recommends that DOE create a full-time, senior position at Headquarters to coordinate hydrogen-related activities within and outside of DOE. The Panel further suggests that the position's effectiveness might be enhanced by having it report to an organizational level higher than the Hydrogen Program – possibly to the DOE Energy Resources Board or the Assistant Secretary of EERE. Position responsibilities would include the development of a coordination plan and publication of an annual coordination report. The report would cover progress in and identify new opportunities for collaboration and leverage of funding.

Outreach

Codes and Standards. HTAP commends the Hydrogen Program for its excellent work in overseeing codes and standards development through cooperation among industry, the NHA, NASA, the International Standards Organization, the National Fire Protection Association, and the Canadian Government. The *Sourcebook for Hydrogen Applications*, derived from this effort, is becoming a valuable reference for the execution of hydrogen energy demonstration and commercialization projects. In general, the work is helping to erode the serious barrier to implementation of hydrogen systems posed by hydrogen safety concerns.

Industry and Public Outreach. While recent publicity on fuel cell vehicles and growing concern about global climate change are helping to enhance awareness of a hydrogen energy option, HTAP believes that a proactive outreach effort by the Hydrogen Program continues to be essential. Potential benefits include increased industry-government collaboration and stronger public support. The Hydrogen Program previously had a strong outreach effort – but that effort has eroded over the past few years, despite Program funding increases, due to increased resource competition for RD&D projects. HTAP encourages the Hydrogen Program to reinvigorate its outreach program, and is pleased that a start has been made in the development of a new outreach plan. One industry outreach goal, for example, is greater awareness and involvement in hydrogen energy by the petroleum industry.

Communication

General. Communication is not a separate activity; it is a part of all topics covered in this report. This report singles out communication as a way of suggesting that the Hydrogen Program could be more effective in communicating activities and results to the hydrogen community. Previous subsections suggest instances where greater communication might lessen negative impressions – such as that the Program lacks proper balance in its portfolio of RD&D projects and is not getting sufficient results from IEA participation. More advantage could be taken, for example, of annual peer review meetings to further communicate Program-level matters to the Program's research community. This includes reports to the entire audience on results of ongoing systems analysis projects (since systems analysis has wide-reaching influence over Program goals), and on international collaboration projects. Moreover, the Program's World Wide Web page – a key communication tool – should be updated frequently.

Peer Reviews. The Hydrogen Program conducts excellent annual peer review meetings of its core R&D

and systems analysis projects. HTAP recommends that the peer review process be extended to cover validation and outreach projects as well. The Panel also recommends that programmatic-level peer reviews be established in some fashion, and include both HTAP and NHA representation. Such reviews had been a regular part of the annual R&D peer review process but were dropped in 1997 due to the increase in individual projects under review and in order to provide more rigorous technical reviews.

3.4 *Program Structure*

This subsection deals primarily with Program management issues pertaining to a middle-level of program management in the Hydrogen Program, the eventual elevation of the Hydrogen Program to a separate office, and the hydrogen centers of excellence. It also presents a self-assessment of HTAP's own effectiveness.

Program Management Structure

The Hydrogen Program has grown from a $1.4 million program in 1992 to over a $16 million program in 1998, with a corresponding increase in the number of RD&D projects. HTAP agrees with the addition of a Team Leader position in 1996 to bolster the Program's senior level of management. However, it disagrees with the decision, made shortly thereafter, to reduce reliance on a middle-level group of task leaders with part-time responsibility for assisting with the management of significant Program areas including systems analysis, production, storage, utilization, and outreach. Now, individual principal investigators need to contact the senior manager level to resolve management-related issues – often with difficulty in making contact, as indicated by the HTAP survey.

Even if a new position for coordination is created, as recommended above, to help lighten the current program management burden, HTAP believes that continued Program growth also calls for restoration of this middle-level with part-time Program management responsibility. As in the past, national laboratory and contractor personnel could fill such part-time positions – as long as assignments avoid any conflicts of interest with RD&D project participation. HTAP further suggests that at least some of the periodic meetings of senior and middle-level Program management also be attended by outside participants, such as representatives from HTAP and the NHA.

Elevation of the Hydrogen Program

Continuing increases in budgets – including industry cost sharing – and the number and size of RD&D projects, should eventually result in a logical elevation of the Hydrogen Program to a separate office within EERE (i.e., the lowest level of organization that uses the "Office" designation within DOE.)

Hydrogen Centers

As mentioned previously in the Introduction and Background section of this report, HTAP recommended the formation of hydrogen centers in the Hydrogen Program. The Panel is pleased with the formation of university-led hydrogen centers of excellence in Florida and Hawaii in June 1997 and looks forward to the future establishment of additional centers for both basic and applied R&D.

HTAP Performance

While HTAP's purview of hydrogen energy matters officially encompasses all of DOE, the Panel recognizes that, for the most part, it has focused almost entirely on the Hydrogen Program within DOE – representing only $16 million compared to over $100 million of related hydrogen research at DOE. One reason has been some lack of awareness by HTAP of hydrogen-related activities in other parts of DOE, as well as in other Federal and state entities. (A notable exception is the fuel cell vehicle program in OTT, where OTT program management regularly participates in HTAP meetings.) Future HTAP meeting agendas should include more hydrogen-related reports and presentations from other DOE offices (FE and ER in particular). Moreover, the addition of a new manager for coordination would significantly expand the Panel's breadth of awareness once that manager begins to closely interact with HTAP membership.

HTAP's effectiveness in advising DOE on strategic and operating matters can be improved by making more use of its Panel meetings to deliberate on important issues and develop recommendations. HTAP needs to increase interaction with DOE to develop meeting agendas that include such issues for Panel deliberation. The inclusion of HTAP participation in appropriate Program management meetings, as suggested above, should also enhance HTAP's awareness and increase its effectiveness in advising DOE.

Preparation of this first HTAP report to Congress has itself added to HTAP's effectiveness. It has brought the Panel closer together in developing member inputs to the report, including conducting the survey. And, it has brought about closer DOE-HTAP interaction as both parties prepared their respective report drafts and reviewed and commented on each other's drafts.

3.5 *Funding and Legislation*

This final subsection first looks at the management and administration of annual funding of Hydrogen Program RD&D projects at both the DOE/Program and the Congressional levels. It then addresses the issue of future Federal hydrogen energy RD&D funding and hydrogen legislation.

DOE and Hydrogen Program Annual Funding

Lack of individual RD&D project funding continuity in the Hydrogen Program has emerged as a major concern, as evidenced by the HTAP survey. The resulting project start/stops have hurt productivity and morale, and can have a serious cash flow impact on participating organizations, especially small businesses. Contributing to the situation are the Congressional mandate of one-year funding (FY 1998) for all energy and water development programs within EERE and DOE management's allocation of crosscutting dollars to cover the cost of managing and administering programs. HTAP believes that crosscutting allocations have been excessive in recent years, cutting significantly into Hydrogen Program funding, and urges DOE to minimize its use. And, to the extent of Hydrogen Program control, the Panel urges the Program to minimize the number of project start/stops.

Disclosure of expenditures is another funding-related issue. Hydrogen Program management should provide HTAP with detailed, project-by-project accounting of how available funds have been allocated. HTAP can better advise DOE if provided with more complete disclosure of expenditures. Moreover, the Panel would like to see disclosure of individual project expenditures, starting at project inception, to the reviewers conducting the annual peer reviews. Provided by Hydrogen Program management in past years, project expenditure histories help reviewers judge accomplishments against dollars spent.

Congressional-Level Annual Funding

The Hydrogen Future Act contains provisions for DOE to use both peer review and competition in the selection of new projects. It also looks to HTAP to advise DOE on project selection. However, Congressional direction in the earmarking of funds for large projects bypasses this selection procedure, and can considerably alter programmatic balance. HTAP would like to discourage project earmarking and would be pleased to offer Congress its opinions on selection of particular projects by providing testimony or by other means. HTAP also suggests that Congress discontinue its current mandate of one-year funding and consider multi-year funding for research activities to increase research productivity.

As a final suggestion on current funding levels for the Hydrogen Program, the Panel urges that both Congress and the Administration fund the Program at the level authorized by the Hydrogen Future Act. HTAP is pleased to see that DOE has submitted a budget request for FY 1999 that more closely approaches the authorized amount than it has in previous years.

Long-Term Funding for Hydrogen Energy

HTAP believes that the goal of supplying significant amounts of renewable energy to the transportation and electricity supply markets in 20-30 years cannot be achieved with current budgets, unless they are highly leveraged with other Federal programs and industry. Realistically, however, HTAP recognizes that funding for current Hydrogen Program goals and plans over the next 3-5 years can be supported at the funding levels authorized by the Hydrogen Future Act, to include continually increasing levels of industry cost-sharing. Beyond 2001, HTAP recommends the extension of the Hydrogen Future Act with comparable yearly funding increases.

In the longer term, it will most likely require major R&D funding increases for hydrogen (and for renewable energy as a whole) to ensure an energy future for the Nation that is secure, sustainable, and environmentally sound. It is hoped that well-developed, widely shared visions of such a future will clearly point the way to needed funding increases – before an energy or environmental crisis does. HTAP will work with DOE to develop such visions (and supporting plans) for hydrogen, which could lead to more aggressive funding recommendations by HTAP in the future.

Legislation

HTAP makes the following three recommendations on legislation:

- **Fund the Hydrogen Program up to the authorized amounts in the Hydrogen Future Act.**
- **Renew the Hydrogen Future Act for an additional five years, to 2006, with annual funding increases comparable to the current Act.**
- **Emphasize hydrogen in new legislation for alternative fuels.** Compared to other alternative fuels, hydrogen provides greater societal benefits, but often at higher costs. There may be circumstances when hydrogen could be given extra help – for example: mandating that Federal fleet vehicles be fueled with hydrogen on government facilities where hydrogen is already handled, such as NASA and Air Force aerospace launch and test facilities; and providing higher incentives and tax breaks for hydrogen than for other alternative fuels, as justified by quantified environmental and other societal benefits.

4.0 Findings

This section summarizes findings from the Analysis of Hydrogen Program Effectiveness section grouped into two subsections: ***Recommendations*** – the report's key findings which HTAP strongly feels should be implemented, and ***Commendations and Suggestions***. The commendations point out many areas where the Program is being effectively managed and executed. The suggestions summarize the report's largely subordinate recommendations and advice for further enhancing Program effectiveness. The order of the individual findings generally follows their order of discussion in the prior section.

4.1 Recommendations

- **Conduct vision setting/scenario development exercises, including workshops.** There continues to be a lack of specific visions and scenarios for mid- to long-term future hydrogen energy systems that link HTAP's long-term vision and the current short-term goals and strategies of the Hydrogen Program. With such visions and scenarios, we can better define future domestic and international markets as well as opportunities for collaboration among Federal, state, and international entities. Moreover, compelling, widely shared visions will enhance both government and public support.

- **Establish a full-time, senior position at Headquarters to coordinate hydrogen energy-related activities.** Coordination needs for hydrogen – a crosscutting technology – within DOE and with other Federal agencies, states, local governments, and foreign countries are extensive. The Hydrogen Program presently lacks sufficient management capacity to carry out effective coordination – the benefits of which include leveraged project funding and technology transfer.

- **Fund the Hydrogen Program up to the authorized amounts in the Hydrogen Future Act.** Past DOE budget requests and Congressional appropriations have been substantially below authorized levels, although DOE's FY 1999 enacted appropriation of $22.25 Million represents a substantial increase over the FY 1998 funding of $15.8 Million.

- **Renew the Hydrogen Future Act for an additional five years beyond 2001, with annual funding increases comparable to the current Hydrogen Future Act that authorized $30.0M in FY 1999; $35.0M in FY 2000; and $40.0M in FY 2001.** The Hydrogen Program's growing portfolio of core R&D and validation projects, which strongly supports the Nation's energy goals, warrants continued funding beyond 2001 at least at the levels of the Hydrogen Future Act.

- **Emphasize hydrogen in legislation for alternate fuels.** Compared to other alternative fuels, hydrogen should be given extra consideration in establishing mandates and incentives, commensurate with hydrogen's greater environmental and societal benefits.

4.2 Commendations and Suggestions

Commendations and suggestions are listed below using the same subsection headings under which they were covered in the Analysis of Hydrogen Program Effectiveness section.

Planning and Systems Analysis – Commendations

- The Hydrogen Program has a strong systems analysis team that utilizes effective methodologies.
- Good progress has been made, especially in scenario analyses of vehicle refueling and stationary power, technical/economic evaluations of core R&D projects, and in publishing a strategic plan.
- A good start has been made on a Technology Roadmap for core R&D and a Validation Plan for validation/demonstration projects.

Planning and Systems Analysis – Suggestions

- Undertake a modest portfolio analysis effort under Hydrogen Program management.
- HTAP supports the PCAST recommendation for a portfolio analysis of all DOE energy R&D under a new portfolio manager position.

Technology Development and Validation – Commendations

- A strong group of technologists at national laboratories, universities, and in industry participates in the Program.
- The Program has a well-balanced portfolio of core R&D and validation projects that encompass both longer-term, renewable-based and nearer-term, fossil-based technologies.
- The core R&D portfolio shows good emphasis on strategic technologies such as photobiological and photoelectrochemical production and advanced storage.
- HTAP supports the Hydrogen Program's efforts to promote direct hydrogen fuel cell vehicles.
- Validation projects have good industry participation and cost sharing with goals that are well-aligned with the goals of the NHA's Commercialization Plan for distributed power and hydrogen vehicles.

Technology Development and Validation – Suggestions

- The report suggests several guidelines for the selection and cancellation of core R&D and validation projects.
- Maintain a balanced portfolio of RD&D projects, if funding levels continue to allow. If not, long-term, renewable-based core R&D needs to be maintained.
- The report suggests guidelines for the execution of validation projects including guidelines on safety, prospects for successful commercialization and/or technology demonstration, and potential outreach opportunities.

Coordination, Outreach, and Communication – Commendations

- Good coordination exists among the Hydrogen Program, OTT, and OBT on PEM fuel cells.
- Promising coordination initiatives have been started with FE, ER, and NASA.
- Very active international coordination within IEA has been underway by the Hydrogen Program over the past several years.
- Good state/local coordination initiatives are underway at Palm Desert, California and at the Nevada Test Site.
- The Hydrogen Program has done excellent work in overseeing the development of hydrogen codes and standards.
- The Hydrogen Program conducts effective peer reviews of its core R&D projects.

Coordination, Outreach, and Communication – Suggestions

- Strengthen and expand coordination with such organizations as FE, ER, NASA, and with state and local government entities.
- Consider having the previously recommended manager position for coordination of hydrogen activities report in at a higher level in DOE than the Hydrogen Program to enhance the position's effectiveness.
- HTAP also supports the PCAST recommendation to create a manager of crosscutting technologies position, which will further strengthen hydrogen coordination within DOE.
- Reinvigorate the Program's outreach effort.
- Strengthen communications with the hydrogen community, including current Hydrogen Program participants.
- Extend peer reviews to validation and outreach projects and to the overall program-level. Involve HTAP and the NHA in, at the very least, the program-level reviews.

Program Structure – Commendations

- A dedicated, hard working management team runs the Hydrogen Program.
- The Program created university-led centers of excellence in Florida and Hawaii in June 1997, in accordance with an HTAP recommendation.

Program Structure – Suggestions

- Restore the part-time, middle-level program management structure that previously existed – making sure to avoid any conflicts of interest with RD&D project participation.
- Periodically involve HTAP and NHA representatives in formal program management meetings.
- Consider the eventual elevation of the Hydrogen Program to the status of a separate office within EERE (i.e., the lowest level of organization that uses the "Office" designation within DOE).
- Expand HTAP's effective purview of DOE hydrogen-energy activities beyond the formal Hydrogen Program, through improved HTAP meeting planning and interaction between HTAP and the recommended new manager position for coordination.
- Expand deliberation of important issues and the development of recommendations at HTAP meetings through improved meeting planning.

Funding and Legislation – Commendations

- DOE management is commended for submitting to Congress a FY 1999 Congressional Budget Request of $24.0 Million for the Hydrogen Program that more closely approached the authorized funding level of $30.0 Million than in previous years.

Funding and Legislation – Suggestions

- Increase the disclosure of RD&D project expenditures to HTAP and to peer reviewers, including any expenditures for crosscutting funds.
- Minimize the frequency of project start/stops due to funding discontinuities.
- Avoid project earmarking. Utilize the normal project selection process and HTAP advice.

5.0 Appendices

Appendix A. HTAP Members and Affiliations

Appendix B. HTAP Timeline

Appendix C. References

Appendix A. HTAP Members and Affiliations

Name	Current Affiliation	Relevant Past Affiliation
Ms. Carol Bailey **	Enron	Southern California Gas
Mr. Addison Bain **	Consultant	NASA
Dr. James Birk **	EPRI	
Dr. Helena Chum	NREL	
Mr. Christopher Flavin	Worldwatch Institute	
Mr. David Haberman	DCH Technology, Inc.	
Mr. Michael Hainsselin	Praxair	
Dr. Mounir Kamal	Consultant	General Motors
Dr. Henry Linden ***	Illinois Institute of Technology	
Dr. Alan Lloyd	Desert Research Institute	So. Coast AQMD
Mr. Frank Lynch **	Hydrogen Components, Inc.	
Dr. James MacKenzie **	World Resources Institute	
Mr. David Nahmias *	Consultant	Air Products
Dr. Roberta Nichols	Consultant	Ford
Dr. John O'Sullivan	EPRI	
Dr. Patrick Takahashi ***	University of Hawaii	
Mr. Henry Wedaa	Consultant	So. Coast AQMD
Dr. Robert Zalosh	Worcester Polytechnic Institute	

* Chairman
** Recent Past Member
*** Member Emeritus

Appendix B.

HTAP TIMELINE

1992

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- First meeting, Jim Birk elected Chairman
- Second meeting

1993

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- Third meeting, three subcommittees formed: 1) Research Priorities 2) Surface Transportation 3) H_2-fueled Aircraft
- Fourth meeting, subcommittee reports presented and published

1994

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- Fifth meeting
- Sixth meeting (held at SCAQMD) Pat Takahashi elected Chairman, Four replacement members join: Carol Bailey, Mike Hainsselin, Mounir Kamal, Alan Lloyd, three new subcommittees formed: 1) Market Applications for H_2-fueled Vehicles 2) Demonstrations 3) H_2 Centers
- Report of the first Chairman (J. Birk) issued

1995

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- Seventh meeting, HTAP Green Hydrogen Report published
- Eighth meeting (held at Hawaii National Energy Institute), Strategic Directions subcommittee formed, H_2-fueled Urban Transit Bus Technology Requirements report published

1996

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- Ninth meeting, Alan Lloyd elected Chairman, Market Applications of H_2-fueled Vehicles report published
- Special international HTAP meeting held at the World Hydrogen Conference in Stuttgart Germany, draft H_2 Centers report published
- Tenth meeting (held at NREL)

1997

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- Eleventh meeting
- Twelfth meeting (held at Lake Tahoe)
- Draft Strategic Directions subcommittee report (HTAP/PATH 2020) published

1998

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

- Thirteenth meeting, David Nahmias elected Chairman, five replacement members join: Chris Flavin, Dave Haberman, Roberta Nichols, John O'Sullivan, Helena Chum Report to Congress subcommittee formed
- HTAP survey report published (for the report to Congress)
- Second special international HTAP meeting held at the World Hydrogen Conference in Buenos Aires, Argentina

"Federal Energy Research and Development for the Challenges of the Twenty-First Century," The President's Committee of Advisors on Science and Technology (PCAST), September 30, 1997.

"Strategic Plan for DOE Hydrogen Program," US DOE Hydrogen Program, January 1998.

"Survey Report," Hydrogen Technical Advisory Panel (HTAP), May 4, 1998.

"The Comprehensive National Energy Strategy," United States Department of Energy, April 1998.

"The Green Hydrogen Report," Hydrogen Technical Advisory Panel (HTAP), May 1995. Also available via the World Wide Web at http://www.eren.doe.gov/hydrogen/graphics/greenhyd.pdf

"The United States Department of Energy's Hydrogen Program – Perspectives from the Hydrogen Technical Advisory Panel (HTAP)," presented at the World Hydrogen Conference, June 1998.