REPORT TO CONGRESS

on the

STATUS AND PROGRESS

of the

DOE HYDROGEN PROGRAM

February 4, 1999

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REPORT TO CONGRESS

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INTRODUCTION

The Department of Energy's (DOE) support of hydrogen-based energy systems was first authorized by the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 (Public Law 101-566). DOE's authorization levels for the Hydrogen Program to the year 2001 was specified in 1996, by the Hydrogen Future Act (Public Law 104-271). The latter Act directs the Secretary of Energy (Secretary) to conduct a research, development, and demonstration program leading to the production, storage, transport, and use of hydrogen for industrial, residential, transportation, and utility applications. In addition, Section 102 of the Hydrogen Future Act requires that: "Not later than January 1, 1999, the Secretary shall transmit to Congress a detailed report on the status and progress of the programs authorized under this Act." This report is submitted in response to that requirement.

In the next 20 years, hydrogen energy systems are expected to penetrate a number of energy markets, to address increasing concerns for global climate change and energy security. Energy Information Administration (EIA) estimates that worldwide carbon dioxide emissions will double from 1998 levels by 2020. Roughly one-third of the U.S. emissions of carbon dioxide come from burning coal and natural gas to produce electricity. Regarding energy security, the U.S. currently imports roughly 45% of the crude oil it consumes, and that percentage is expected to increase to 60% by 2015.

Industry is fully cognizant of the potential of hydrogen and is investing very substantially in developing fuel cells and hydrogen production systems for several markets including the hydrogenation of fuels. Advances in high-efficiency Proton Exchange Membrane (PEM) fuel cell technology have attracted significant private sector interest and investment as an electricity generation technology for both stationary and mobile applications. There are plans to commercialize both a 250 kW fuel cell system for utilities and 5 kW residential fuel cell system by 2002. The automobile industry is expected to be producing commercial buses by 2002 and tens of thousands of cars annually by 2004, that will utilize the PEM fuel cell as the onboard power system. These efforts will enhance the commercialization of PEM fuel cells and ultimately help to establish carbon-free, zero-emission energy systems.

Given the President's budget submissions, and within the authorization levels of the Hydrogen Future Act of 1996, the Hydrogen Program supports a broad range of research and development (R&D) projects that together aim to make producing, storing, and using hydrogen in integrated energy systems safer and less expensive than it is today. In concert with mid-term market factors and long-term sustainability goals, criteria for the production, storage, and utilization of hydrogen were established for the hydrogen core R&D program. Progress on several projects in the R&D pipeline show promise to move to the validation stage over the next few years (e.g., advanced natural gas- and biomass-based hydrogen production technologies, high pressure gaseous and cryogas hydrogen storage systems, and reversible PEM fuel cell systems). Others lay the groundwork for longer-term opportunities.

The federal role in technology validation must enhance the utilization of hydrogen in the energy generation and transportation sectors, but not duplicate industry activities that are in their mainline businesses. Concerning transportation applications, the Secretary of Energy's Hydrogen Technical

Advisory Panel, in their report [Market Applications for Hydrogen-fueled Vehicles, April 1996], indicates that barriers to the introduction of the hydrogen option include the lack of a refueling infrastructure, limited driving range, and lack of affordability. On the utility side, a key program need is the demonstration of integrated renewable and hydrogen systems to provide increased operational and peaking generation flexibility. These are also the areas where industry is under-investing. The DOE Hydrogen Program, in partnership with industry, has developed a 50/50 cost-shared technology validation effort for the demonstration of renewable-hydrogen systems, hydrogen infrastructure, and small-scale remote power systems to overcome these barriers and offer potentially attractive options for emerging electric generation and transportation markets.

STATUS AND PROGRESS

In January 1998, the DOE Hydrogen Program published a strategic plan that established the goals and strategic objectives that are used to manage the Program. Five-year implementation plans were derived for four of the Program elements: research and development; technology validation; policy, planning, and analysis; and outreach and coordination. The status and progress of each of these elements is discussed below.

Technology Development

R&D is the fundamental thrust of the Hydrogen Program and the basis for achieving all of its long-term goals. The R&D projects are organized into three categories: hydrogen production; hydrogen storage, distribution, and delivery; and hydrogen utilization. Exhibit 1 presents an overview of the R&D Program and shows some of the top-level component performance goals that are used to manage the research projects. Each of the R&D categories is described below.

Hydrogen Production: Production R&D is focused on developing more efficient and less costly conversion processes, and on developing smaller-scale production systems that are amenable to distributed-generation and vehicle applications. Exhibit 1 displays the cost goals established by the program to meet requirements for mid-term and long-term applications. Experimental results in the Sorption Enhanced Reformer (SER) and Plasma Reformer projects demonstrate the potential for lowering the cost of hydrogen production by 25 to 30% from conventional steam reforming processes that will meet the system goals contained in Exhibit 1. The targets for systems that harness solar power directly to produce hydrogen by splitting water will be more difficult to achieve, but the potential pay-off, a carbon-free energy system, justifies sustained commitment. Moreover, several recent advances show promise.

Hydrogen Storage, Distribution, and Delivery: R&D is focused on novel hydrogen storage systems that are lighter, smaller, and less costly than existing alternatives. For the mid-term, Thiokol, in a cooperative agreement with DOE, has designed and fabricated lightweight "conformable" pressure vessels that are expected to exceed 7 weight percent (wt%) gaseous hydrogen storage. Also, the first-cycle testing of a cryo-gas system that can potentially double the vehicle range offered by pressurized tanks has been successfully completed by Lawrence Livermore National Laboratory. For the longer term, in 1998 researchers identified a sodium-aluminum hydride storage system with hydrogen uptake at 5-10 wt%.

Hydrogen Utilization: R&D is focused on PEM fuel cell systems that convert hydrogen to electricity, as well as ancillary equipment needed for complete systems. Stack testing of a non-machined low-cost fuel cell demonstrated a 57% energy conversion efficiency. Also, success with sensors demonstrating improved hydrogen selectivity and response speed have enabled prototype

Exhibit 1. Summary R&D Roadmap Matrix

	Goal	Relevant Projects
Hydrogen Production	1. Lower the production cost of hydrogen to \$6-8/MMBtu *Fossil-based*	Sorption-enhanced reformer Ion-transport membrane Plasma reformer Thermo catalytic cracking
	Biomass-based	Fast pyrolysis and catalytic steam reforming High-moisture biomass gasification Bacterial water shift
	2. Lower the production cost of hydrogen to \$10-\$15/MMBtu *Solar/water-based*	Photobiological Photocatalytic water cleavage Photoelectrochemical-based direct conversion
Hydrogen Storage, Distribution, Delivery	3. Demonstrate safe and cost-effective storage systems for use in stationary and vehicle applications: Storage density, 5 wt% H_2, Full life cycle cost, 50% of the cost of hydrogen fuel	Pressurized containers Cryogenic pressurized containers Magnesium and calcium-based chemical hydrides Aluminum-based chemical hydrides Fullerenes, carbon nanotubes, and graphite nanofibers
Hydrogen Utilization	4. Develop fuel cell and reversible fuel cell technologies as an efficient, low-cost means of converting hydrogen into electric power	Low-cost PEM fuel cell manufacturing techniques Fiber-optic chemochromic and thick-film hydrogen sensors

subsystem engineering tests to be planned for 2000 and 2001 to transfer the technology to industry. PEM fuel cell projects funded by the Hydrogen Program are complementary to efforts within industry and the DOE Office of Transportation Technologies.

Technology Validation

The Technology Validation effort is devoted to integrating first-of-a-kind advanced hydrogen production and storage technologies, incorporating the latest industry-developed fuel cell technology, and validating the overall energy systems' performance. The rationale for the technology validation program is predicated on two factors: 1) significant R&D progress has been achieved or is expected on several hydrogen production and energy storage technologies, and 2) significant industry and government investment in fuel cell technology will require infrastructure development and energy systems improvements if they are to be integrated within a hydrogen energy system.

Based on progress of the core R&D, system requirements defined both through analysis and industry interest, DOE has recently completed a Technology Validation Plan in three categories (Renewable Hydrogen Systems, Hydrogen Infrastructure, and Remote Power Systems), with the following goals:

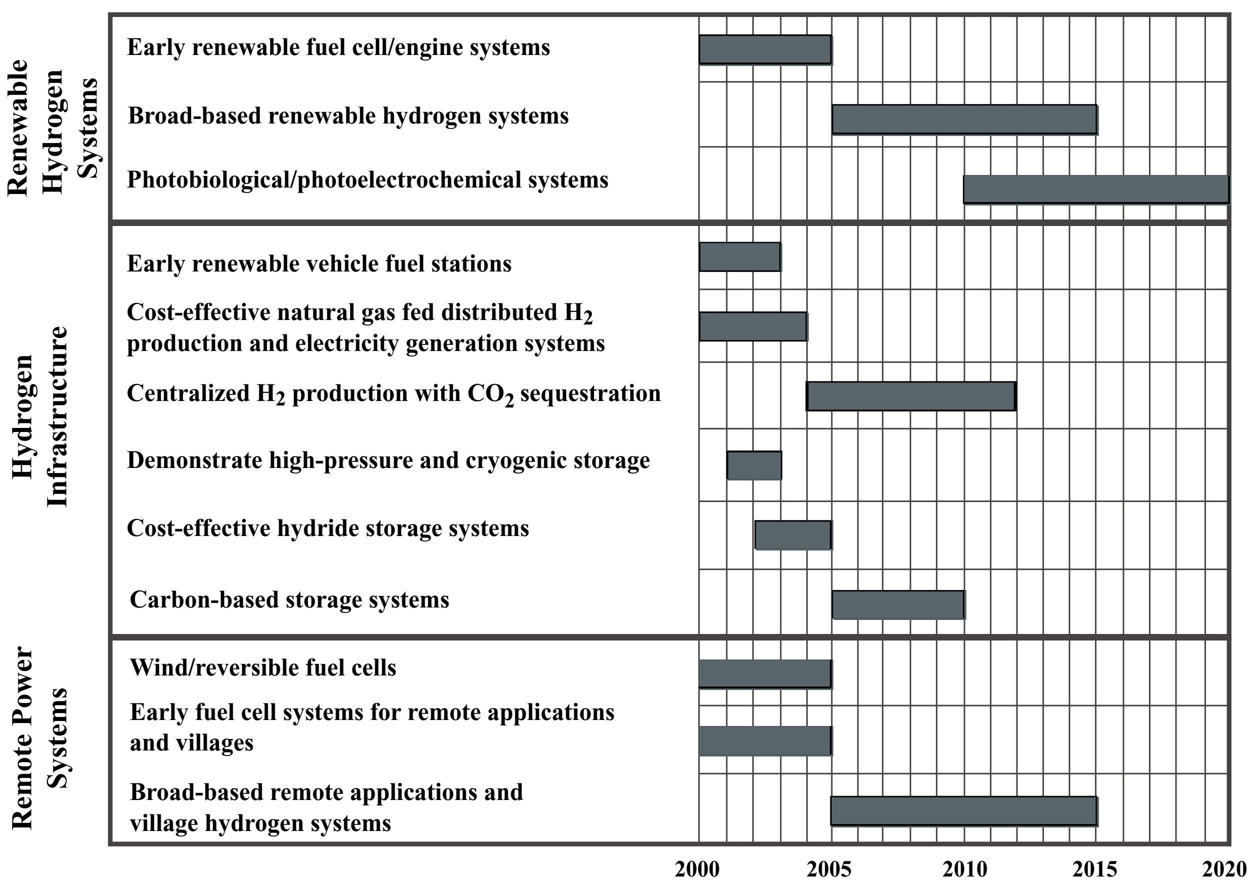
- Low-cost production of hydrogen from fossil and biomass-based fuels at distributed sites;
- Cost-effective carbon sequestration hydrogen production options for fossil-based fuels at centralized sites;
- Low-cost hydrogen storage for stationary and vehicle applications;
- Cost-effective fuel cell options, including a reversible fuel cell, that accommodate renewable energy sources; and
- Remote and village power systems.

Exhibit 2 shows a time line of Technology Validation projects with both mid-term goals to be achieved by 2005, and long-term goals by 2020. The actual execution of the technology validation program will depend on the progress toward meeting the core R&D program goals, the prospective effectiveness of several of the intergrated system approaches, acceptance by the private sector as a market option, and market opportunities (i.e., green power, equivalent zero emission vehicles, etc.). Each technology validation project will be reviewed annually to ensure that the projects continue to meet the criteria.

Renewable Hydrogen Systems: These projects aim to validate the utilization of hydrogen storage in renewable electricity generating systems. Projects scheduled to receive support include a concentrating solar power (dish/Stirling engine) system to extend the solar operation into evening, a photovoltaic/electrolysis system that will use the sun's energy to produce both electricity and hydrogen fuel for motor scooters, and a wind and/or photovoltaic electrolysis system for grid-independent applications.

Hydrogen Infrastructure: The co-production of electricity and hydrogen fuel from natural gas at distributed sites offers tremendous advantages for cost-effective energy systems. The distributed

Exhibit 2. Hydrogen Technology Validation Plan



electricity can serve both commercial and residential applications while the hydrogen fuel can be used in transportation. Demand for hydrogen fuel is being created as investments by developers and communities seeking low-emission vehicles result in several low-cost vehicle options, such as extended range electric vehicles and hydrogen/methane combustion vehicles. Several major projects are slated to validate this concept and provide hydrogen to these communities over the next few years, including: a renewable hydrogen on-site electrolysis project at the Palm Springs (CA) airport, and a solicitation to validate the combined hydrogen fuel/electricity concept in Las Vegas (NV).

Remote Power Systems: This area is focused on PEM fuel cell systems, conceived as units that can provide both electricity and heat for buildings and residences. This is being closely coordinated with the Russian American Fuel Cell Consortium and the Remote Power Initiative projects for Arctic applications. Contracts have been awarded to two companies for the development of small (4-5kW) residential fuel cell systems as well as an advanced reversible fuel cell that may be integrated with a wind energy system to enable high-penetration wind energy systems.

These projects will define new consensus standards and certification tests and will provide the operating experience necessary to determine whether hydrogen energy can compete in the energy marketplace as a safe and effective fuel.

Environment

An analysis of the full life-cycle emissions of carbon dioxide and criteria pollutants from various clean car alternatives including PEM fuel cell, hybrid electric, natural gas, diesel and battery vehicles showed that direct-hydrogen fuel cell vehicles using hydrogen produced from natural gas and stored onboard provide the lowest emissions. Direct hydrogen fuel cell vehicles using hydrogen from renewables generate zero emissions.

Policy, Planning, and Analysis

The Hydrogen Program benefits from an ongoing analysis effort that provides an understanding of the issues associated with bringing hydrogen energy systems to the market and the trade-offs among the many different hydrogen technology options with respect to emissions, efficiency, and economics.

The text box on the following page presents several key analytic results that contributed to direction of the core research and development, and technology validation activities.

Recent Analysis Efforts That Have Had an Important Impact on Program Direction

A study of transportation and storage options compared distributed-versus-centralized hydrogen systems and found that the compression and storage of gaseous hydrogen at a distributed fueling station saved approximately $4.50/MMBtu over a centralized system.

Analysis showed that a system in which gas-station-size natural gas processors provide compressed hydrogen gas to vehicles is less costly than systems in which natural gas, methanol, or gasoline are processed onboard the vehicle. The co-product option offers fuel and electricity costs of $1.20/gallon equivalent gasoline and 6 cents/kWh.

Detailed modeling and cost analysis of advanced biomass gasification and pyrolysis technologies have shown that hydrogen production costs can be reduced to $8/MMBtu by extracting valuable co-products from intermediate process streams and using agricultural residue feedstock. As such, the use of biomass resources represents a premier renewable strategy for the production of hydrogen.

An evaluation of infrastructure and fuel storage requirements for remote inland Alaskan villages indicated that a PEM fuel cell that co-produces electricity and heat provides a 40% reduction in diesel fuel consumption compared to the current system of diesel internal combustion engine generators and

Outreach and Coordination

The strategic objectives for outreach and coordination are to identify key constituencies and prepare materials and tools to keep them informed about hydrogen, and to coordinate Program efforts with other DOE offices and governmental agencies. A number of these activities have already begun or are ongoing, including:

- Within the Office of Energy Efficiency and Renewable Energy, a Special Assistant to the Assistant Secretary was given the responsibility for coordinating and integrating interdepartmental activities associated with the PEM fuel cell. A workshop was held in October of 1997 with participants representing transportation, electric generation, and industry sectors. This effort has enabled the Offices of Transportation, Building and Utility Technologies to produce a coordinated set of program goals and milestones.
- Collaborative activities are being co-funded and co-managed with the Office of Fossil Energy for carbon sequestration and the production of hydrogen from low Btu coal, and with the Office of Energy Research in reviewing long-term R&D programs.
- At the state and local level, hydrogen technology demonstration activities within non-attainment areas, such as the Palm Desert/Palm Springs community, are taking place along with additional efforts to promote and educate the public about the utilization of hydrogen.
- The Hydrogen Program participated in three workshops held by the National Aeronautics and Space Administration (NASA) on future programs and activities aimed at developing a hydrogen airplane.
- The Hydrogen Program recognized three academic institutions as “Centers of Excellence” and maintains an active graduate student research program at these institutions.

INTRODUCTION

This Report to Congress characterizes the status and progress of the Hydrogen Program in two parts. Part 1.0, Background, provides the situation analysis for program activities and describes the strategic plan and implementation plans.

Part 2.0, Program Status and Progress, describes the current efforts on the basis of the goals and strategic objectives established in the Hydrogen Program Strategic Plan.

1.0 BACKGROUND

Situation Analysis

A significant driver creating opportunities for the introduction of hydrogen in energy markets is the worldwide concern over global climate and Federal/State regulations on air quality. EIA estimates that the carbon dioxide emissions will grow from 4,836 MMT to 10,447 MMT by 2020. Also, by 2020, the Energy Information Agency (EIA) 1998 International Energy Outlook projects that: U.S. petroleum imports will increase to 65% of the projected 24.4 million barrels per day consumed and U.S. imported oil will double from today's levels. Hydrogen generation can be produced from domestic fossil or renewable resources which would contribute to national security. Whether it is initiatives to reduce greenhouse gases as proposed by the ongoing international environmental negotiations or State statutes, there is mounting pressure to adopt clean energy options. Using hydrogen has the dual advantage of reducing both particulate and greenhouse gas emissions.

Industry is fully cognizant of the potential of hydrogen and is investing very substantially in developing fuel cells and hydrogen production systems for several markets including the hydrogenation of fuels. Hydrogen use can be expected to increase for transportation and electric generation applications as advanced technologies such as fuel cells are commercialized and their costs decline. However, the ability to penetrate the marketplace will depend greatly on reducing the cost of producing hydrogen, on being able to store it effectively onboard vehicles, the cost of fuel cells and the ability to use innovative solutions to hydrogen infrastructure and renewable hydrogen systems that provide cost effective systems.

The world-automobile industry is investing more than one billion dollars to develop a cost-effective PEM fuel cell for an electric vehicle powertrain. Daimler-Benz and Ford have invested more than $750 million in Ballard Power Systems with the goal of reducing fuel cell automotive powerplant costs and putting commercial vehicles on the road by 2004. Other companies including General Motors, Toyota, and International Fuel Cells have also launched programs to commercialize fuel cell cars, with General Motors committing to introduce such vehicles by 2004.

The electricity industry has also recognized the potential for fuel cells to deliver clean, quiet, and cost-effective premium electricity. GPU International and other partners have formed a joint venture with Ballard Power Generation to produce 250 kW fuel cells by 2002. Several consortia have been formed to produce 5 kW residential fuel cells in the same time frame. Other industries in Japan, Europe and the U.S. have also joined the race to develop cost-effective PEM fuel cells for various electricity markets.

Industrial gas companies such as Air Products and Chemicals, Inc. and Praxair are investing in new technologies to reduce the cost of delivered hydrogen. Today hydrogen is produced in large industrial gas plants and delivered to customers by truck or pipeline. To be cost competitive with other fuels in the future, hydrogen will need to be produced at the customer site in distributed systems using reformers or electrolyzers. Advanced technologies including ion transport membrane reformers, sorbent enhanced reformers, catalytic wall reformers, are being developed by the industry with the goal of reducing hydrogen costs at the customer's site by 25 percent.

Implementation Plans

The Strategic Plan for the DOE Hydrogen Program (dated January 1998) establishes the overall goals and strategic objectives of the Program by which four five-year implementation plans are developed for four of the five areas of goals established in the Strategic Plan. The area without its own implementation plan, environment, is addressed throughout the other four implementation plans. The fifth goal are environment. The four implementation plans include the: Research and Development (R&D) Roadmap; the Technology Validation Plan; the Policy Planning and Analysis Plan; and the Outreach and Coordination Five Year Plan. The Annual Operating Plan provides a one-year detail-level activity plan for the activities established in the implementation plans. The Annual Operating Plan is developed from these documents and is used to manage the program.

The *R&D Roadmap* provides a multi-year projection of current and planned activities relevant to the Technology Development area of the Program. It is developed with industry input of their proposed research and development plans and schedules for each project that defines component and subsystem experiments, economic analyses and critical milestones. Experimental results are reviewed in a formalized annual process for their compliance to programmatic criteria.

The *Technology Validation Plan* presents a set of projects selected from planned competitive solicitations for 50/50 cost-shared projects that were issued in the areas of hydrogen infrastructure systems, renewable hydrogen systems, remote power systems and hydrogen business opportunities. The validations conducted by the Program focus on promising technologies or integrated systems that enhance unique hydrogen utilization in transportation and electric generation applications which also demonstrate cleaner and more sustainable systems. The timing of future validation projects will be based on the accomplishments of the Core Research and Development program and relevant external market factors.

The *Policy, Planning, and Analysis Plan* establishes the parameters for the technical and business analyses to provide the most effective and efficient path toward achieving the goals of the Program and of national energy strategy. Specific analyses conducted by the Program in this area include: market analyses, portfolio analyses, technical and economic analyses, and performance metric studies. This plan will be reviewed annually to define the specific studies to be conducted.

The *Outreach and Coordination Five Year Plan* addresses the outreach and coordination goals of the Program. This plan establishes the guidelines by which the Program initiates and maintains efforts in education, industry partnerships, stakeholder relations and government coordination activities with other federal agencies, state and local entities and other Department of Energy offices.

The *Annual Operating Plan* characterizes in detail all programmatic activities scheduled to occur in the current fiscal year, provides project descriptions and specifies relevant criteria that the project is required to meet.

2.0 STATUS AND PROGRESS

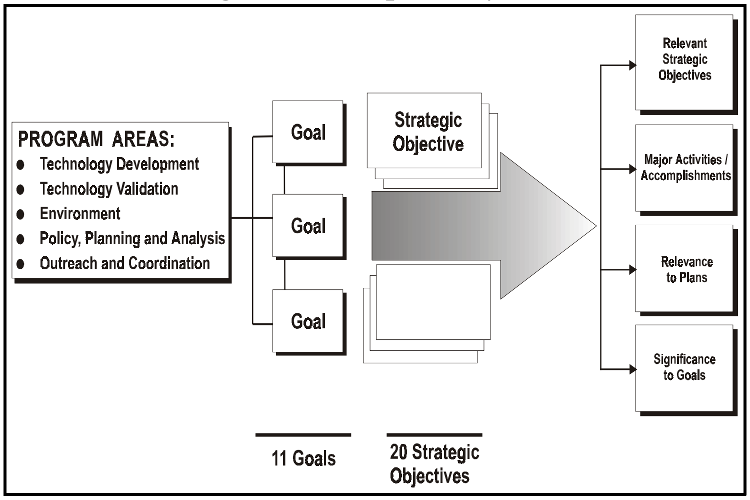
This Report describes the status and progress of each goal in the terms depicted in Figure 2-1.

2.1 Technology Development Goals

The Strategic Plan establishes four technology development goals which relate to the three major components of the R&D program established in the R&D Roadmap. These components include:

- Hydrogen Production;
- Hydrogen Storage, Distribution, and Delivery; and
- Hydrogen Utilization.

Figure 2-1. Report Layout



As shown in Figure 2-2, "Summary R&D Roadmap Matrix," many technologies are being investigated in each goal area. To ensure that the proposed R&D is worthy of continued support, threshold criteria and annual performance reviews are used to manage the activities. Threshold criteria are relevant to promising hydrogen applications in the electric generation and transportation areas. Each of the goals depicted in Figure 2-2 will be evaluated as to the results achieved, relevance of results to implementation plan, and their significance to the goal.

Figure 2-2. Summary R&D Roadmap Matrix

	Goal	Relevant Projects
Hydrogen Production	1. Lower the production cost of hydrogen to \$6-8/MMBtu *Fossil-based*	Sorption-enhanced reformer Ion-transport membrane Plasma reformer Thermo catalytic cracking
	Biomass-based	Fast pyrolysis and catalytic steam reforming High-moisture biomass gasification Bacterial water shift
	2. Lower the production cost of hydrogen to \$10-\$15/MMBtu *Solar/water-based*	Photobiological Photocatalytic water cleavage Photoelectrochemical-based direct conversion
Hydrogen Storage, Distribution, Delivery	3. Demonstrate safe and cost-effective storage systems for use in stationary and vehicle applications: Storage density, 5 wt% H_2, Full life cycle cost, 50% of the cost of hydrogen fuel	Pressurized containers Cryogenic pressurized containers Magnesium and calcium-based chemical hydrides Aluminum-based chemical hydrides Fullerenes, carbon nanotubes, and graphite nanofibers
Hydrogen Utilization	4. Develop fuel cell and reversible fuel cell technologies as an efficient, low-cost means of converting hydrogen into electric power	Low-cost PEM fuel cell manufacturing techniques Fiber-optic chemochromic and thick-film hydrogen sensors

Hydrogen Production

***Goal* – Improve the efficiency and lower the cost of fossil-based and biomass-based hydrogen production processes to $6-8/MM Btu.**

Fossil-Based Projects

Relevant Strategic Objectives:

- Demonstration of advanced natural gas-based distributed hydrogen production technologies with higher efficiencies and lower capital cost than conventional steam methane reforming that serve transportation and utility sector applications.
- Demonstration of large-scale central hydrogen production processes serving transportation and utility sector applications.

Major Activities and Accomplishments:

Fossil-based hydrogen production systems serve as a transitional method to renewable hydrogen production technologies as they become more cost effective. Using natural gas, and coal and coal bed methane sources, hydrogen can be produced using a variety of novel processes that offer significant improvements over conventional practices.

In the *Sorption Enhanced Reformer (SER)* process at Air Products and Chemicals, Inc. research and development is underway to develop a process in which the reaction of methane and adsorption of carbon dioxide occur simultaneously. This shift in the equilibrium composition allows the process to occur efficiently at lower temperatures than conventional steam methane reforming. The advantage over conventional processes is a significantly lower cost, a smaller size reactor and a simplification of the sequestration process by providing a clean, purified source of carbon dioxide. Recent results are:

- Demonstrated in a single reactor over 82% conversion of natural gas to produce a product stream with 98% purity prior to conventional cleanup via pressure swing absorption;
- Developed and demonstrated a hydrocalcite carbon dioxide adsorbent with capacities in excess of 0.5 millimoles, CO_2 per gram adsorbent at 400ºC; and
- Identified second family of promising carbon dioxide adsorbents.

In the *Ion Transport Membrane (ITM)* syngas process under research and development at Air Products and Chemicals, Inc., ceramic membrane systems will purify oxygen from air while simultaneously reforming natural gas to hydrogen and carbon dioxide. The process as designed produces syngas (carbon monoxide and hydrogen) from natural gas in a single continuous process with costs that are 30-50% lower than conventional production processes. This is a new project and is a collaboration with the Office of Fossil Energy.

The *Plasma Reformer* work being performed by the Massachusetts Institute of Technology (MIT) focuses on developing an economical and compact plasma reformer for the production of hydrogen from hydrocarbons. The advantages of plasma reformers, as compared to conventional technologies, include: higher power density; greater fuel flexibility; faster response time; simpler materials required for construction; and higher conversion efficiencies. Key recent results of this project include:

- Demonstrated hydrogen production system with low CO content (~3 to 5%) with power densities of ~10kW (H_2 HHV)/liter of reactor; and
- Improved plasmatron design to use less than 10% of the energy for conversion.

The *ThermoCatalytic Cracking* project of the Florida Solar Energy Center focuses on a one-step thermocatalytic decomposition (TCD) of natural gas into hydrogen and carbon. Since TCD of natural gas does not produce any CO_2 emission, it can be considered as a transition process linking the fossil fuel and the renewable energy resource-based economies. This project was reinitiated only recently and has not reported results to date.

Relevance of Accomplishments to Implementation Plan:

Based on the recent accomplishments noted above and the Technology Roadmap planning activity, the following implementation schedule was developed (Figure 2-3):

Figure 2-3. Fossil-Based Hydrogen Production Technologies

Technology	Performer	Short-Term Goals	Technology Validation
Sorption-Enhanced Reformer (SER)	Air Products and Chemicals	By 2000: operate the PDU to demonstrate performance of process; and be able to complete economic evaluation of process	By 2001: candidate for deployment at refueling station
Ion-Transport Membrane (ITM)	Air Products and Chemicals	By 2001: complete subsystem engineering development and testing, process design on syngas reactor, and material selection	By 2002: candidate for deployment at refueling station
Plasma Reformer	Massachusetts Institute of Technology	By 2000: design integrated process system; test optimum system using natural gas	By 2002: candidate for refueling station solicitation
Thermo Catalytic Cracking	Florida Solar Energy Center	By 2001: production of hydrogen-rich gas (>85%) with CO < 100ppm	By 2004: candidate for refueling station solicitation

Significance of Results to Goal:

The results achieved in the Sorbent Enhanced Reformer and the Plasma Reformer are on track with the goal established for these systems of $6 to 8/MMBtu and reducing the cost of hydrogen production by 25%. These projects and the two other systems all provide smaller systems with simpler materials of construction, less cost and higher efficiencies. Also, importantly, the proposed systems all offer the means to separate hydrogen from the carbon stream and thereby offer superior means to consider the sequestration of carbon or carbon dioxide.

Biomass-Based Projects

Relevant Strategic Objective:

- Demonstration of biomass / municipal solid waste (MSW)-based hydrogen production processes.

Major Activities and Accomplishments:

Biomass-based systems offer the opportunity to produce hydrogen from renewable resources at competitive costs in the mid-term (5-10 years). Three biomass-based projects are being supported to achieve the goal using a variety of agricultural wastes and biomass grown specifically for energy.

In the *Biomass to Hydrogen via Fast Pyrolysis and Catalytic Steam Reforming* project at the National Renewable Energy Laboratory and the Jet Propulsion Laboratory, research and modeling focuses on processing technologies for the production of a bio-oil, that like petroleum, contains a wide spectrum of components. These components can be transformed into hydrogen via catalytic steam reforming at lower temperatures than conventional systems. The production of hydrogen with key high-value co-products derived using this process has the potential to produce inexpensive hydrogen from biomass. Three key results of this project include:

- Demonstrated conversion of bio-oil to hydrogen in a bench-scale fixed bed reactor;
- Achieved hydrogen yields of up to 85% of stoichiometric amount in a fixed bed (bench scale); and
- Developed predictive kinetic model for the determination of product distribution from biomass pyrolysis.

The *Hydrogen Production from High Moisture Content Biomass in Supercritical Water* project of the University of Hawaii focuses on producing hydrogen from wet biomass. The process can handle biomass without the need for a costly drying operation and opens up a wide variety of high-water-content feedstocks such as water hyacinth and banana trees. The near-term objective of the project is the identification of appropriate slurry compositions and to improve the performance of the catalytic, supercritical gasification reactor to enable scale-up by industry. Key recent results are:

- Developed simplified and reliable method for feeding wet, particulate biomass as a paste into a supercritical flow reactor; and
- Demonstrated the catalytic supercritical steam reforming of biomass to hydrogen, CO_2, some methane and trace CO.

In the *Hydrogen Production via Bacterial Water Gas Shift* project at the National Renewable Energy Laboratory, microorganisms isolated from nature are used to reduce the level of CO to below detectable levels (0.1 ppm) at temperatures of around 25-50ºC in a single reactor. This process provides the ability of a single-step gas conditioning step for converting thermally generated, raw fuel gases in hydrogen-rich, CO-free gas streams suitable for direct injection into hydrogen fuels cells without additional cryogenic, PSA, or other gas purification steps. Key recent results are:

- Developed a novel gas-phase carpet bioreactor for high-rate shift of CO to hydrogen; and
- Identified strains of thermophilic bacteria that can perform the water-gas shift reaction at temperatures of around 50°C.

Relevance of Accomplishments to Implementation Plan:

Based on the recent accomplishments noted above and the Technology Roadmap planning, the following implementation schedule (Figure 2-4) was developed.

Figure 2-4. Biomass-Based Hydrogen Production Technologies

Technology	Performer	Short-Term Goals	Technology Validation
Biomass to Hydrogen via Fast Pyrolysis and Catalytic Steam Reforming	National Renewable Energy Laboratory	In 1999: Achieve catalyst lifetime of >24 hours while maintaining 80% yield In 2002: Optimize process demonstration unit (PDU) and identify industrial partner	By 2003: Candidate for engineering development unit with industrial partner
Hydrogen Production from High Moisture Biomass	Hawaii Natural Energy Institute	In 1999: Convert > 90% of the feedstock without any carbon buildup In 2000: Scale-up reactor to 1 inch diameter with internal heating	Under review
Bacterial Water Gas Shift	National Renewable Energy Laboratory	In 1999: Operate at higher pressure and test reactor designs for improved performance In 2001: Construct and operate pilot plant	By 2002: Construct and operate demonstration plant with industrial partner

Significance of Results to Goal:

Analysis of the National Renewable Energy Laboratory pyrolytic reactor project indicates that, with the appropriate co-product strategy, hydrogen can be produced for $6-10/MMBtu depending on the cost of the feedstock. In this process, the hydrogen can be produced at or near the point of use, thereby significantly reducing current costs. The initial estimates for the analysis of the High Moisture Biomass project plans will be formulated pending that review. The industrial demonstration of the Water-Gas Shift Bioreactor process is a planned activity based on existing information and projected system economic analyses that it can contribute to meeting program goals.

***Goal* – Advance emission-free, and renewable-based hydrogen production technologies towards commercial viability, with a target cost of $10-15/MM Btu.**

Solar/Water Based Projects

Relevant Strategic Objectives:

- Continue research and development of photoelectrochemical and photobiological hydrogen production processes, focusing on improved solar efficiency.

Major Activities and Accomplishments:

The use of solar energy to split water into hydrogen and oxygen is an attractive means to directly convert solar energy to chemical energy. Biological, chemical, and electrochemical systems are being investigated as long term (>10 years), high-risk, high-payoff technologies for the sustainable production of hydrogen. Four direct-production technologies are under investigation to achieve the goal and relevant strategic objective.

In the *Photobiological Production of Hydrogen* project, scientists from Oak Ridge National Laboratory, the University of California Berkeley, Hawaii Natural Energy Institute and the National Renewable Energy Laboratory are applying classical and molecular genetic techniques to green alga systems capable of sustained photobiological production of hydrogen in air. In an effort to understand how these organisms could be used to produce large quantities of hydrogen, various reactor designs are under development. Key results are:

- Isolated mutant strains of *Chlamydomonas reinhardtii* with increased oxygen tolerance of 470% over parental strain;
- Corroborated the single photosystem mechanism for hydrogen production for some systems;
- Operated a photobioreactor for 18 months in a continuous hydrogen production mode;
- Measured photosynthetic productivity that was 6-7 times greater than the normally pigmented cells; and
- Screened 100 mutant algal clones for enhanced hydrogen production in a single eight hour day.

In *Development of New Materials and Approaches to Photocatalytic Systems*, the Florida Solar Energy Center, in conjunction with the University of Geneva (Switzerland) and NIMC (Japan) is investigating tandem/dual bed photosystems using sol/gel-deposited tungsten trioxide films for the solar-driven decomposition of water to hydrogen and oxygen. The potential advantages of these systems are low manufacturing cost, safe evaluation of hydrogen and oxygen in separate compartments, and more efficient use of the solar spectrum. A key result for this effort is:

- Identification of component families that have suitable electronic energy level characteristics of oxidative photocatalytic water splittings.

The *Generation of Hydrogen from Photocatalytic Cleavage of Water* of the University of Oklahoma addresses three problems in improving the efficiency of using the cleavage of water to form hydrogen and oxygen. These include: the narrow range of wavelengths which are absorbed by titania to initiate the reactions; the difficulty of combining photoaccessibility and reactant accessibility to high surface areas of the photocatalyst; and the efficiency of the subsequent catalytic (versus photocatalytic) steps to form hydrogen and oxygen. This project is in its first year.

In the *Photoelectrochemical (PEC)-Based Direct Conversion Systems for Hydrogen Production*, the National Renewable Energy Laboratory (NREL) and the Hawaii Natural Energy Institute (HNEI) are investigating the use of PEC devices to split water in a one-step process for the production of hydrogen using solar irradiation. NREL's approach is to use the most efficient semiconductor materials available, consistent with the energy requirements for a water splitting system that is stable in an aqueous environment. HNEI is pursuing a low-cost amorphous silicon-based tandem cell design with appropriate stability and performance. Significant results for the collaborative project are:

- Operated a PV/PEC water splitting system with a solar-to-hydrogen world-record efficiency of 12.4% (lower heating value, LHV) using concentrated light, for over 20 hours;
- Performed an outdoor test of the a-Si cells, resulting in a solar-to-hydrogen efficiency of 7.8% LHV under natural sunlight; and
- Developed an advanced electronic circuit model for the design of multijunction a-Si cells for 10% solar-to-hydrogen conversion efficiencies.

Relevance of Activities to Implementation Plan:

Significant progress has been made in establishing world records for the efficiency of PEC devices and defining techniques to efficiently produce oxygen resistant organisms that produce hydrogen. This enables performance scaled experiments in the next two years to define the economic potential of those technologies.

Figure 2-5. Photoelectrochemical and Photobiological Hydrogen Production Processes

Technology	Performer	Short-Term Goals	Technology Validation
Photobiological Production of Hydrogen	Multiple (NREL, UH, ORAL, UCB)	In 2000: operate lab-scale 2-stage Hawaii process; research 10% oxygen tolerant mutant and 30% reduction of antennae complexes	Targeted long-term validation selection
New Materials and Approaches to Photocatalytic Systems	Florida Solar Energy Center	In 1999: employ photocatalytic compounds in particulate form in various configurations to effect solar-driven decomposition of water	Targeted long-term validation selection
Photocatalytic Cleavage of Water	University of Oklahoma	In 1999: synthesize and characterize catalysts	Targeted long-term validation selection
Photoelectrochemical (PEC)-Based Direct Conversion Systems	National Renewable Energy Laboratory University of Hawaii	In 2000: build 20 x 20 cm^2 module; research greater than 8–10% efficient a-Si cell; develop catalyst	Targeted long-term validation selection

Significance of Results to Goal:

Direct solar-to-hydrogen research is in the early stages of evaluation. Initial process analyses have been performed to identify the key cost drivers for the photobiological and photoelectrochemical systems. Analyses of the economic viability of these processes will be undertaken in the near future. Initial analysis indicated that photoelectrochemical processes produced hydrogen at a cost of $25/MMBtu – which is higher than the goal of $10–15/MMBtu. However, there have been significant process improvements in photoelectrochemical and photobiological production of hydrogen as well as greater photosynthetic productivity. Thus, there is potential to further reduce the cost associated with these technologies and produce limitless hydrogen when fossil fuels become more limited. These activities will continue to be supported at levels recommended by the President's Committee on Advance Science and Technology as a preeminent strategy for when fossil supplies are limited.

Hydrogen Storage, Distribution, and Delivery

***Goal* – Demonstrate safe and cost-effective storage systems for use in stationary distributed electricity generation applications, and for on-board and stationary applications in urban non-attainment areas.**

Relevant Strategic Objectives:

- Facilitate the use of hydrogen as a vehicular fuel through (a) modeling and experimental studies to verify the safety of high-pressure gas storage and (b) developing advanced storage technologies for on-board applications.
- Develop lower cost storage technologies and demonstrate their competitiveness in integrated renewable energy systems.

Major Activities and Accomplishments:

Lightweight and high-energy-density storage will enable the use of hydrogen as a transportation fuel. Efficient and cost-effective stationary hydrogen storage will permit PV and wind to serve as more dispatchable power systems. Eight projects dealing with hydrogen storage technologies are supported by the DOE Hydrogen Program to achieve the goal and relevant strategic objectives.

Currently, compressed gas is the only commercially available method for ambient-temperature hydrogen storage on a vehicle. Carbon fiber-wrapped polymer cylinders achieve higher densities (15 kg/m3 and 5 wt%) than conventional fiber-glass wrapped aluminum cylinders. Advanced lightweight pressure vessels have been designed and fabricated by researchers at Lawrence Livermore National Laboratory.

The *Hydrogen Storage in Pressurized Gas Container Systems* project, involves the development of lightweight bladder liners that act as inflatable mandrels for composite overwrap and as permeation barriers for gas storage. These tank systems are expected to exceed 30 kg/m^3 and 10 wt% hydrogen storage (at room temperature) when fully developed. Recent results by the LLNL conformable tank research team include:

- Designed and fabricated lightweight pressure vessels with state-of-the-art performance factors;
- Worked with industry partners to design the storage/vehicle interface and a new generation of tank liners.

Additional research is underway at the Lawrence Livermore National Laboratory to develop *Insulated Pressure Vessels for Hydrogen Storage on Vehicles.* These insulated, high-pressure, low-temperature insulated hydrogen tanks are superior to conventional liquid hydrogen tanks and give increased flexibility to the refueling infrastructure. Analysis indicates that these insulated hydrogen tanks have significant volume, range, and energy efficiency advantages over conventional high pressure tanks, do not incur the full energy penalty of conventional liquid tanks, and have greatly enhanced dormancy capability. Recent results by the LLNL insulated hydrogen tank research team include:

- Developed a detailed thermodynamic model of the insulated hydrogen pressure vessel and determined the best operating conditions; and
- Successfully completed the first cycle testing of the high-pressure, low-temperature of Kevlar-Aluminum storage vessels.

Conventional high capacity metal hydrides, generally based on magnesium systems, require high temperatures (300-350°C) to liberate hydrogen, but sufficient heat is not generally available in transportation applications. Low temperature hydrides, generally transition metal-based, however, suffer from low gravimetric energy densities (about 1 wt%) and require too much space on board or add significant weight to the vehicle. Sandia National Laboratories and Energy Conversion Devices are developing low-temperature metal hydride systems that can store 3-5 wt% hydrogen and have high volumetric densities. Key results are:

- Developed and fabricated a modular hydride bed for a 5 kW application;
- Identified a hydride manufacturing technique that drastically improve alloy yield and hydrogen sorption kinetics; and
- Identified a number of alloy compositions that can store 5 wt% hydrogen.

In the *Catalysed Complexes for Hydrogen Storage* project at the University of Hawaii, researchers are investigating the use of catalytically-doped $NaAlH_4$ as a storage material on board vehicles. Although thermodynamically favorable, the $NaAlH_4$ dehydrogenation reaction kinetics are very slow and the complete reverse reaction is possible only under severe conditions. In order for this hydride to be a practical material suitable for vehicular applications, kinetic enhancement of the dehydrating process is required. This can be achieved with catalysts such as titanium or polyhydride complexes. Polyhydride complexes that catalyze the dehydrogeneration reaction of cycloalkanes and are unusually robust have been identified. This suggests that these complexes may also act as catalysts for the reversible dehydrogenation of $NaAlH_4$. The use of titanium as a dopant has also been investigated. Key results for the University of Hawaii and its international and industrial partners include:

- Developed a new method for introduction of titanium into $NaAlH_4$, with markedly improved kinetics;
- Measured dehydrogenation rates at temperatures as low as 100°C and rehydrogenation to >5 wt% at 170°C; and
- Patent awarded for dehydrogenation process using organometallic catalysts.

In *Hydrogen Transmission/Storage with a Metal Hydride/Organic Slurry*, a new approach for the production, transmission, and storage of hydrogen using a hydride slurry as the hydrogen carrier and storage medium is under investigation by Thermo Power Corporation. The organic slurry protects the hydride from premature and overly rapid contact with moisture and makes the hydride pumpable. At the point of storage and use, a hydride/water reaction is used to produce high purity hydrogen. An essential feature of the process is recovery and reuse of spent hydride at a centralized processing plant. Research issues include the identification of safe, stable and pumpable slurries and the design of an appropriate high temperature reactor for regeneration of spent slurry. Recent results include:

- Investigated cost-effective and technically acceptable organic slurry liquids;
- Completed engineering design and early economic analyses of the proposed process that indicates an ancillary benefit of a favorable hydrogen production cost; and
- Evaluated lithium hydride and calcium hydride for potential use in hydride slurries.

Carbon-based hydrogen storage materials that can store significant amounts of hydrogen at room temperature are under investigation (i.e., carbon nanostructures and C_{60} fullerenes). Two carbon nanostructures are of interest, single-walled nanotubes and graphite nanofibers. In the National Renewable Energy Laboratory's *Carbon Nanotube Materials for Hydrogen Storage* project, single-walled carbon nanotubes, elongated pores with diameters of nanometer dimensions (length/diameter > 12), adsorb hydrogen by capillary action at non-cryogenic temperatures. Significant results for the research team include:

- Produced single-walled nanotubes in high yields using a laser synthesis technique;
- Demonstrated hydrogen uptake at 5-10 wt% on a nanotube basis at room temperature.

At Northeastern University, researchers are investigating *Hydrogen Storage in Carbon Nanofibers*. Graphite nanofibes are a set of materials that are generated from the metal catalyzed decomposition of hydrocarbon-containing mixtures. The structure of the nanofibers is controlled by the selection of catalytic species, reactant composition, and temperature. The solid consists of an ordered stack of nanocrystals that are evenly spaced at 0.34–0.37 nanometers (depending on preparation conditions). Northeastern University indicates that excellent hydrogen storage capacities are possible in these structures. Research results include:

- Produced 5-gram quantities of graphite nanofibers of varying structures; and
- Tested gram-sized samples for hydrogen adsorption characteristics.

At Oak Ridge National Laboratory and Material and Electrical Research (MER), researchers are investigating the *Fullerene Option* for high-weight-percent hydrogen storage. Experimental results indicate that over 6 wt% hydrogen can be absorbed by C_{60} fullerene, that the absorbed hydrogen can be released by heating, and that the rates of the absorption/desorption process can be tailored by the use of various catalysts. Key results include:

- Demonstrated that >6 wt% hydrogen could be charged at 180°C and 350–400 psi; and
- Demonstrated the dehydrogeneration of fullerene hydride at <225°C in the presence of a catalyst.

Relevance of Accomplishments to Implementation Plan:

Based on the recent accomplishments noted above and the Technology Roadmap planning activity, the following implementation schedule was developed (Figure 2-6):

Figure 2-6. Hydrogen Storage Systems

Technology	Performer	Short-term Goals	Technology Validation
Pressurized containers	LLNL	In 1999: design and fabricate conformable hydrogen storage tank	In 2000: conduct validation of system components with industry partner
Insulated pressurized containers	LLNL	In 1999: design, fabricate and test a tank for a vehicle	In 2000: demonstrate on vehicles
Hydride development	SNL and ECD	In 1999: demonstrate 5 wt% (material basis) @ <150 °C in the lab; build lightweight storage tank with 3.5 wt% (system basis) storage	In 2000: build light weight storage modules for hydrogen bus with 3.5 wt% (system basis) storage
Hydride/organic slurry	Thermo Power Corp.	In 1999: verify regeneration of hydride; conduct bench-scale tests of slurry production, pumping, and storage In 2000: conduct detailed engineering study	In 2002: investigate as candidate for demonstration of a refueling station

Technology	Performer	Short-term Goals	Technology Validation
Catalysed complexes	University of Hawaii	In 1999: determine cycling effects, operating parameters In 2001: develop low-cost storage system fabrication	In 2001: build light weight storage module for hydrogen bus with 4.5 wt% (system basis) storage
Fullerenes	RAL	In 1999: demonstrate 7 wt% (material basis) storage at low temperature (<220 °C) In 2002: test and validate prototype storage equipment	Investigate as a demonstration on a vehicle depending on experimental results
Carbon nanotubes	NREL	In 1999: continuously produce nanotubes @ >50% yield In 2001: store 6 wt% (material basis) hydrogen at room temperature; perform cycling and stability testing	Investigate as a demonstration on a vehicle depending on experimental results
Carbon nanofibers	Northeastern University	In 1999: verify reported hydrogen capacity In 2000: develop continuous production technique In 2001: store 6 wt% (material basis) hydrogen at room temperature; perform cycling and stability testing	Investigate as a demonstration on a vehicle depending on experimental results

Significance of Results to Goal:

The DOE Hydrogen Program supports a number of projects in the development of improved hydrogen storage for vehicular and electric generation applications that have potential to meet acceptable cost, volumetric and gravimetric energy density criteria. The projects described above, if successful, will provide several candidates for transportation and energy-generation applications with the required hydrogen storage, in safe and cost effective systems early in the next decade. It is expected that advance pressurized and cryo-gas tank concepts will be demonstrated on vehicles in 2000–2001. By 2001 high weight percent (4.5%) and low temperature (190ºC) dehydrogenation metal hydride systems should be available for certain applications and that an attractive metal hydride/slurry system could be a candidate by 2002. By 2004 a room temperature carbonaceous storage system with > 6 wt% should be available for vehicle storage. Economic analyses have been performed on a number of the storage concepts, and areas for cost improvements have been identified. Detailed cost analyses will be performed as the research advances.

Hydrogen Utilization

Goal – **Develop fuel cell and reversible fuel cell technologies as an efficient low-cost means of converting hydrogen into electric power.**

Relevant Strategic Objectives:

- Develop a low-cost fuel cell and reversible fuel cell.
- Enable the development of more reliable, less expensive sensors.

Major Activities and Accomplishments:

Proton exchange membrane (PEM) fuel cells could provide low-cost, high-efficiency electric power, and could be operated “in reverse” as electrolyzers to generate hydrogen. In order to increase the market penetration in both the transportation and utility sectors, additional improvements in manufacturing and advanced systems are required. The DOE Hydrogen Program supports three projects in the development of advanced fuel cell systems and two projects in the development of hydrogen detection technologies.

The *Low-Cost Fuel Cells* project (Polymer Electrolyte Fuel Cells) of the Los Alamos National Laboratory focuses on developing and demonstrating a 4 kW, hydrogen-fueled polymer electrolyte fuel cell stack, based on non-machined stainless steel hardware and on membrane/electrode assemblies of low catalyst loadings. The stack is designed to operate at ambient pressure with a design which enables operation at higher fuel pressure, if required. This is to be accomplished by working jointly with a fuel cell stack manufacturer, based on a Cooperative Research and Development Agreement. The performance goals are > 50% energy conversion efficiency hydrogen-to-electricity (DC) at a power density of 0.9 kW/liter for a stack operating at ambient inlet pressures. The cost goal is <$600 kW, based on present materials costs. Key recent results of this project include:

- Developed a new, non-machined fuel cell stack of 2.2 mm in diameter for small applications;
- Demonstrated a current density of 0.3 A/cm_2 at 0.7V, 57%, energy conversion efficiency hydrogen-to-electricity (DC)—the laboratory projects stack packaging at close to 1 kW/liter at this energy conversion level with significantly less than 10% parasitic power loss; and
- Began testing short stack in April 1998.

Unitized regenerative fuel cells, where the fuel cell can also be operated “in reverse” as an electrolyzer, offer advantages over systems using a separate electrolyzer for reactant generation and a separate fuel cell for power generation. H_2/halogen regenerative fuel cells are capable of higher round-trip efficiency than H_2/O_2 or H_2/air, and are appropriate for stationary applications whereas the H_2/O_2 and H_2/air are suitable for transportation applications. At the Lawrence Livermore National Laboratory, researchers are investigating the development of H_2/O_2 and H_2/air *Regenerative Fuel Cell Systems*. Design issues for the reversible fuel cell system include membrane improvement, thermal management, humidifcation, and catalyst type and loading. Key results for LLNL and its industrial partners are:

- Operated regenerative H_2/O_2 fuel cell in the fuel cell mode at a current density of with >1000 A/ft^2 at 0.6 V;
- Demonstrated rapid cycling between electrolyzer and fuel cell mode (<1 minute round trip); an
- Prepared new facility for wider range of pressure and electrochemical testing.

SRT Group is investigating the *Production of HBr for Off-peak Electrolytic Hydrogen Production***,** where hydrogen is produced in a two-step hybrid process. The first step is a reaction between bromine, methane, and steam, which produces HBr and CO_2. The second step is the electrolysis of the HBr in a very efficient reversible fuel cell/electrolyzer to produce bromine and hydrogen. The bromine is recirculated and the hydrogen is stored for future use in the fuel cell or for sale as fuel. The fuel cell also produce electricity by recombining the bromine and hydrogen into HBr. Recent research results include:

- Tested laboratory-scale bromine-steam-methane reactor, with effective conversion; and
- Generated HBr concentrations of 13M and conversion rates approaching 95% at 750°C.

Hydrogen leak detection is an essential element of safe systems. In collaboration with an industrial partner, the development of low-cost fiber optic and thick film sensors by the National Renewable Energy Laboratory and the Oak Ridge National Laboratory, respectively, will provide affordable and reliable options for hydrogen safety systems. At NREL, a *Low-cost Fiber-optic Chemochromic Hydrogen Detector* uses optical fibers with a thin film coating in the end that changes optical properties upon reversible reaction with hydrogen. Changes in the reflected light signal is an indication of the presence of hydrogen. Sensitivity and selectivity are important research issues. Significant results include:

- Designed and constructed a portable hydrogen sensor capable of canceling out most of the signal noise caused by fiber flexing (as would occur with vibration in a vehicle);
- Received patent on the surface plasmon resonance design approach; and
- Received Hydrogen Technical Advisory Panel 1997 Research Success Story Award.

ORAL's *Low Cost Hydrogen Sensors* project is focused on the development of monolithic, resistive thick film sensors that are inherently robust, selective to hydrogen, and easy to manufacture. They rely on a change in the electrical resistivity of a layer of paladium in the presence of hydrogen. Research issues include developing appropriate techniques for active (versus traditional passive) thick film applications. Research results include:

- Tested sensor materials for durability and stability;
- Developed coatings to protect sensors from adsorbed water and oxygen; and
- Modified the design for sensor metallization to reduce power consumption by a factor of 4.

Relevance of Accomplishments to Implementation Plan:

Based on the accomplishments noted above and the Technology Roadmap Plan, the following implementation schedule is expected (Figure 2-7):

Figure 2-7. Reversible Fuel Cells

Technology	Performer	Short-term Goals	Technology Validation
PEM fuel cell	LANL	In 1999: operate 4 kW stack in a mobile and/or stationary platform In 2000: fabricate 25 kW fuel cell for integration into a stationary power system	In 2001: transfer technology to industry
Regenerative fuel cell	LLNL	In 1999: test alternative membranes and catalyst mixtures for performance improvement	In 2002: transfer technology to industry
HBr fuel cell	SRT Group	In 1999: fabricate and test 50 kW bench-scale HBr electrolyzer unit In 2000: scale up designs for 100 kW integrated system	In 2001: conduct 100 kW energy storage demonstration
Fiber-optic sensor	NREL	In 1998: complete prototype design, fabrication, and testing	In 1999: field test fiber optic sensor with industry partner
Thick-film sensor	ORAL	In 1999: optimize next generation of solid state sensor In 2000: complete prototype design, fabrication, and testing of next generation solid state sensor	In 2000: field test solid state sensor with industry partner In 2001: field test next generation of solid state sensor with industry partner

Significance of Results to Goal:

Improvements to existing fuel cell designs and manufacturing techniques will reduce the capital costs and increase the efficiency of these efficient energy conversion devices consistent with the $600/kW goal. Unitized fuel cell/electrolyzer systems can further reduce the required investment. Researchers are investigating areas that will, if successful, result in efficient, inexpensive, emission-free energy conversion devices.

The development of hydrogen sensors for vehicular and other applications is an essential element in the effort to reach the goal of the safe use of hydrogen. Both detector projects have an industrial partner and are aggressively pursuing demonstration of their technologies. These designs are expected to be transferred to industry.

2.2 Technology Validation Goals

The Hydrogen Program strategy includes the periodic release of solicitations to industry in order to obtain industry's buy-in to the various hydrogen technologies. It is necessary to require industry to provide substantial business plans as well as cost sharing in order to participate. Industry's promoting public awareness is another requirement

***Goal* – Support industry in the development and demonstration of hydrogen systems in the utility and transportation sectors.**

Relevant Strategic Objectives:

Obtain industry participation through competitive solicitations;

- Integrate renewable energy resources with hydrogen storage in remote distributed power scenarios;
- Demonstrate hydrogen production, storage, and refueling stations within several clean clusters for targeted applications (i.e., airports, industrial vehicles, government vehicles, etc.); and
- Demonstrate hydrogen-based operating experience acceptable to safety officials.

As a result of collaboration with industry, the following areas have been identified as mid term market opportunities that are derivative from the strategic objective: 1) renewable hydrogen systems, including renewable electricity in remote areas; 2) hydrogen infrastructure; and 3) remote and village power systems.

The figure below summarizes the three validation programs and their respective goals established in the Technology Validation Plan.

Figure 2-8. Hydrogen Technology Validation Projects

Validation Programs	Relevant Goals
Renewable Hydrogen Systems	Distributed Renewable Power Generation (i.e., wind, solar, thermal, PV) using reversible and PEM Fuel Cells in remote and grid applications Biomass-to-hydrogen production
Hydrogen Infrastructure	Hydrogen refueling infrastructure providing fuel equal to \$0.60–1.20 / gallon of gasoline equivalent and electricity @ 5 to 6¢/kWh Co-production of electricity and fuel for vehicles in residences Hydrogen production from low-cost coal with carbon sequestration Industrial and airport fuel cell vehicles; shuttle buses with hydrogen / compressed natural gas mixture.
Remote and Village Power Systems	Multi-fuel processor / combined power and heat for villages and remote applications

As documented in the Technology Development section of the Report, there are significant core R&D goals that can be achieved in the next five years. Achieving these goals will provide several significant benefits:

- low-cost production of hydrogen;
- carbon sequestration for fossil- and biomass-based fuels;
- low-cost hydrogen storage for stationary and vehicle applications; and
- low-cost fuel cell options, including a reversible fuel cell that accommodates renewable energy systems.

In addition, the industry is aggressively pursuing PEM fuel cell vehicles and electricity generation systems by 2002. Thus, the validation of new, integrated systems in the utility and transportation sectors will show that hydrogen has mid-term potential, and will lead toward achieving the longer-term goals. On the utility side, a key program need is the demonstration of technologies that will integrate hydrogen with renewable resources. This can be provided, for example, by the integration of a wind turbine, electrolyzer, hydrogen storage device, and gen set to provide less expensive peak power to a remote location. In the transportation sector, clean hydrogen clusters can be developed. These will consist of a limited infrastructure that will produce and use hydrogen. A near-term example might be the use of small-scale steam reforming, partial oxidation, or plasma reforming to convert natural gas to hydrogen at the site of a refueling station. The hydrogen is then pressurized, stored and transferred to on board storage system on a fleet of vehicles. It then powers these vehicles through either fuel cells or hybrid internal combustion engines. Industrial, corporate and airport vehicles are prime target opportunities.

During the course of the Program, other hydrogen-based energy options not addressed in the plan to 2004 will be evaluated. These could include hydrogen-fueled aircraft, boats or trains. The Program must continue to monitor these potential markets and provide support where appropriate.

The ultimate measure of hydrogen safety will be the development of new consensus standards, certification tests, and demonstrated operating experience acceptable to safety officials and regulations. Hydrogen validation projects must address these issues.

The figure below specifies the validation projects and the industrial partners and the potential solicitations for future projects in the three program areas:

Figure 2-9. Projects Relevant to Validation Programs

Validation Programs	Relevant Projects
Renewable Hydrogen Systems	• Renewable/Hydrogen Utility Systems – Solar Thermal – Proton Energy – Wind and Photovoltaics for Islands – Energy Partners – Wind for Alaska – Desert Research Institute • Reversible Fuel Cell for Alaska – TBD • Photovoltaics / Hydride Storage – Energy Conversion Devices • Biomass to Hydrogen Gas – (2003)
Hydrogen Infrastructure	• Solicitation for Refueling Station in Nevada – TBD • Renewable Refueling Station – Sunline Bus Co., Teledyne Brown • Electrolysis – Stuart Energy • Advanced Refueling Station – TBD • Second Generation Advanced Refueling Station – TBD • Lab Mock-up of Prototype Reformer System (2000) • Conversion of Buses to H_2/CH_4 Mixture – TBD • Industrial Fuel Cell Vehicle – Southeastern Technology Center • Conformable Tanks – Thiokol • Cryo Gas Tank – SCI • Chemical Hydride Tanks – Thermo Power Corp.
Remote and Village Power	• Village Power – Teledyne Brown • Village Power – Northwest Power

Renewable Hydrogen Systems

Major Activities and Accomplishments:

The projects relevant to this validation program include: Solar Thermal; Wind and Photovoltaics for Islands; Wind for Alaska; Reversible Fuel Cell for Alaska; Photovoltaics / Hydride Storage; Landfill Gas; and the Biomass to Hydrogen Gas project.

The *Solar Thermal* project by Proton Energy and partners involves constructing two distinct integrated renewable hydrogen energy systems. The Phase One system will take power from a renewable source, generate hydrogen from a proton exchange membrane (PEM) electrolyzer and store it for use in generating power from a Stirling engine/generator on demand. In Phase Two, fuel cell technology will be used to demonstrate the commercial viability of producing dispatchable power from a fuel cell instead of a combustion engine / generator. Future plans focus on developing a unitized regenerative fuel cell by 2002.

The *Wind and Photovoltaics for Islands* project by Energy Partners involves the development of an integrated renewable hydrogen fuel cell power system which also consists of an electrolyzer, hydrogen and oxygen storage systems, and controller/power conditioning unit. Some of the hydrogen produced may be used as a fuel for land vehicles or boats.

The *Wind for Alaska* project by the Desert Research Institute and partners will evaluate a hydrogen utility energy storage system for two potential applications. The first is an isolated system providing continuous electricity from wind turbines for a remote community. The second is a grid-connected wind turbine system using hydrogen storage to adjust to load needs based on demand and economics. The project will develop optimization tools consisting of design and operational models to show the economic and technical performance of any integrated renewable system at any worldwide location. From the performance and cost data collected, industry partners will explore approaches for establishing a manufacturing capability in integrated hydrogen utility systems for niche applications.

The *Reversible Fuel Cells for Alaska* project – the contractor to perform this project remains to be determined (TBD) – focuses on evaluating a utility-scale energy storage system using a regenerative electrolyzer/fuel cell based on hydrogen bromide chemistry. The 100 kW system will provide peak power to an isolated hydroelectric grid, recharging from the hydroelectric turbines during off-peak periods. Early markets for hydrogen bromide electrolysis include merchant hydrogen vendors and their customers with a need for high reliability hydrogen supplies, but volumes too low to justify current captive production methods. Development of modular components will decrease costs associated with one-of-a-kind installations.

The *Photovoltaics / Hydride Storage* project by Energy Conversion Devices, Inc., integrates the small-scale production, storage, and use of hydrogen energy from intermittent renewable sources. Combining low-cost amorphous silicon photovoltaics with high-pressure electrolysis and high volumetric-density metal hydride storage can produce renewable hydrogen on-demand for a variety of residential uses. The resulting system can take advantage of the inherent modularity of the various component technologies to produce units sized to particular consumer needs. This project will support the commercialization of a 100–2,000 Watt photovoltaic / electrolysis / storage system to provide a pollution-free alternative to many common household fuel uses in developing countries, such as motor scooters, cooking, heating, and electricity. In addition, this effort could result in a system to co-produce on-demand electricity for residential customers from a renewable source.

***Relevance of Accomplishments to Implementation Plan*:**

Through the solicitation process, industry has responded with a wide range of renewable hydrogen systems for early niche markets that is to be cost shared on a 50/50 basis. Future biomass projects are still to be established and a landfill project is under consideration for award to complete the full gamut of renewable-hydrogen options that are attractive. The results anticipated in these integrated and unique system configurations will contribute significantly to understanding the future technical and economic viability of renewable-based hydrogen systems**.**

***Significance of Results to Goals*:**

All of these projects were initiated recently and are not scheduled to report results yet. Based on the business plans submitted as part of the evaluation process, each is expected to result in the establishment of hydrogen options in niche markets with sales in the 2002 to 2005 timeframe.

Hydrogen Infrastructure

Major Activities and Accomplishments:

The ten projects relevant to this validation program include: Refueling Station with Coproduction of Hydrogen and Electricity (solicitation) Renewable Refueling Station; Electrolysis; Advance Refueling Stations; Lab Mock-up of Prototype Reformer System; Industrial Fuel Cell Vehicle; Methane/hydrogen vehicles; Conformable Tanks; Cryo Gas Tank; and the Chemical Hydride project.

A *Solicitation for a Refueling Station* project in Nevada will seek to demonstrate the performance, availability and cost of a facility that coproduces electricity (through a 50 kW PEM fuel cell) and hydrogen that is pressurized and stored for use in vehicles. Alternative fueled vehicles that operate on hydrogen will be used as transportation systems in Las Vegas, at the Nevada Test Site and at Nellis Air Force Base.

The *Renewable Refueling Station* project by Teledyne Brown Engineering and Sunline Bus Company will develop a clean and sustainable transportation system based on hydrogen fuel produced from renewable resources. Taking advantage of an existing infrastructure for personal transportation vehicles, the municipal government will convert an existing natural gas fleet of buses towards natural gas/hydrogen and hydrogen fuel cell vehicles. An existing solar-powered/electrolysis system will be transferred for use at Palm Desert, CA. In addition, there are significant wind turbines in the area that produce electricity which will be purchased to electrolytically produce hydrogen for the vehicles.

The *Electrolysis* project by Stuart Energy involves developing two models of electrolytic hydrogen generators, one each for transit fleet and home applications. Based on well-established electrolyzer technology, these systems will provide cost-effective, home-based hydrogen for refueling personal vehicles as well as a larger refueling station sized system for fleet vehicles. The home-based system avoids the high costs and technical risks of on-board fuel reformers while offering the consumer the convenience of at-home refueling and a full tank of fuel every morning. Production of the home-based system could achieve over 140,000 units by 2007. This system will also establish a refueling infrastructure that is compatible with fleet vehicle and bus operation and could represent an early transition option. Vehicle mandates, like the one in California and development of fuel cell vehicles, could establish a market sizable enough for this technology.

Projects are planned in 2001 and 2002 for *Advanced Refueling Stations* which will include candidates that have been shown technologically and economically viable through key subsystem engineering tests being conducted in the core R&D program. When experiments are conducted on the plasma reformer and the thermocatalytic reformer then a solicitation for a plasma reformer or thermocatalytic refueling station project will be considered to demonstrate systems compatible with carbon sequestration.

Manufacturers are considering 5 kW PEM fuel cell units for residences. In an approach similar to the coproduction of electricity and hydrogen in refueling stations, an alternative small system that can produce hydrogen for power and heat for small buildings or residences will be considered. A *Lab Mock-up of a Prototype of Reformer System* will be fabricated and operated to determine specific performance, safety and reliability issues associated with the production of hydrogen in such an environment.

The *Conversion of Buses to H_2/CH_4 Mixture* project, by NRG, will demonstrate the environmental benefits of converting existing buses that operate on natural gas to ones that utilize 30% hydrogen/ 70% natural gas. The project will establish hardware and engine control strategies that will allow mixtures of hydrogen and natural gas to achieve near-zero exhaust emissions, demonstrated in an on-road vehicle.

The *Industrial Fuel Cell Vehicle* project by Southeastern Energy Technology Center integrates hydrogen storage and utilization technologies with off-road light industrial vehicles such as forklifts and utility carts. These vehicles will be powered by PEM fuel cells with on-board metal-hydride storage. This high-value niche market currently uses battery-powered vehicles to satisfy stringent work-place emission requirements. The fuel cell will increase the working range of these vehicles from approximately two hours to a full eight hour work day while producing no harmful or dangerous emissions. This will produce significant value-added to industry through increased productivity and decreased down-time. This technology would compete for about half of the market for electric, light industrial vehicles. By the year 2005 this market will be approximately 10,000 units. Such high volume production reduces fuel cell and metal-hydride storage costs sufficiently to make these systems economically viable. Development of a sizable hydrogen fleet will also result in the growth of a hydrogen refueling infrastructure. Modular components will decrease costs associated with one-of-a-kind installations.

Thiokol's *Conformable Tanks* project involves the construction and testing of composite or fiberglass tanks in other than cylindrical tank configurations to improve the overall volume constraints in vehicles. The carbon/epoxy filament wound tanks will be certified for 5000 psi pressure operation. The tanks will store 1.62 kg of hydrogen at a greater than 7 wt% ratio to the tank system.

The *Cryo Gas Tank* project by SCI involves the construction and testing of low-temperature, high-pressure gaseous hydrogen storage vessel. The vessel will handle temperatures as low as 20° K and pressures as high as 5000 psi. These vessels have packaging characteristics similar to those of conventional, low-pressure liquid hydrogen tanks, with much reduced venting losses. This option gives increased flexibility to the fueling infrastructure in that both pressurized hydrogen and liquid hydrogen are applicable fuels and is expected to provide vehicles with a 350 mile range capacity.

The *Chemical Hydride Tanks* project by Thermo Power Corp. will develop an integrated hydrogen production, distribution, and refueling system based on the storage of hydrogen in chemical hydrides suspended in an organic slurry. This concept offers the potential of a high weight percent hydrogen storage medium, low-cost production, and distribution infrastructure using a recyclable liquid. Byproduct hydroxide slurry is collected at the refueling station and regenerated at a central facility using low-cost biomass or other carbon heat source.

***Relevance of Accomplishments to Implementation Plan*:**

The ten projects in the Hydrogen Infrastructure Technology Validation effort address every major issue involved in establishing hydrogen as a safe, cost-effective option. The activities are expected to be implemented from 2000–2004 with attractive options that have the potential to fill niche markets. It is anticipated that the range of viable refueling stations and vehicle storage concepts explored will set the basis for wider utilization of hydrogen vehicles for fleet vehicles and buses during the demonstration period. Additional vehicles will need to be demonstrated when more advanced storage concepts such as carbonaceous systems become available.

***Significance of Results to Goals*:**

The oldest of these projects is less than two years old and none is scheduled to report significant results yet. The integrated system concepts proposed for distributed and centralized generation should decrease the cost of developing a hydrogen infrastructure. The distributed system is based on the coproduction of electricity (from a 50 kW PEM fuel cell) and hydrogen. This approach greatly reduces the cost to produce hydrogen, transfers some of the infrastructure costs to the electric generation mission and permits a development schedule based on the electric option for decreasing costs due to mass production. For the centralized concept, the utilization of chemical hydride storage systems on the vehicle portends a volumetric and gravimetric storage approach as well as a low cost hydrogen generation system using low cost coal or biomass feedstocks. The cryo-gas tank can provide for a system where cryogenic hydrogen is used to double the range of the vehicle but the lower cost, high pressure hydrogen can be used for shorter trips. Both the conformable high pressure tank and the cryo-gas tank exceed the 5% weight goal (i.e., 7% and 10%). Range-extended electric vehicle and shuttle buses operating on a mixture of hydrogen and natural gas are expected to find selected sales in niche markets.

Remote and Village Power

Major Activities and Accomplishments:

The two relevant projects to this validation program include:

The *Village Power* projects, by Teledyne Brown and Northwest Power focus on proving the concept of a clean PEM fuel cell using hydrogen obtained from distillate fuel oil (diesel or kerosene) to provide grid-quality primary power to remote consumers in Alaska. Compared with internal combustion diesel engines currently supplying this market, these 3-5 kW systems provide safe, clean, efficient, and low-noise electricity while utilizing a wider variety of potential fuel sources (including the fuel oils currently used). The Teledyne Brown concepts uses a partial oxidation reformer to produce the high-purity hydrogen necessary for the reliable operation of the PEM fuel cell. The Northwest Power system uses a steam reformer fuel processor, which produces high-purity hydrogen using a novel, internal, two-stage purifier, and yields high power output from the PEM stack and a relatively simple balance of plant. Participants will install the systems in 2000, including the fuel cell stack, steam reformer, power control system, and power conditioning system, in a remote residence or commercial establishment in Alaska. These tests will prove system functionality and provide a basis for commercial scale production.

Relevance of Accomplishments to Implementation Plan:

The two projects will contribute significantly to the future technical and economic viability of hydrogen-based remote and village power systems by lowering diesel consumption and electric generation/heating costs.

Significance of Results to Goals:

These projects were initiated recently and are not scheduled to report results yet. The system concept employed uses the cogeneration capacity of the fuel cell system to provide both heat and power, and water. This would be advantageous in minimizing the infrastructure necessary for a household. Analyses have shown that this approach can provide electricity for 15 cents/kWh.

2.3 Environmental Goals

The program addresses its two environmental goals through the activities of the other four goal areas. That approach reflects that these environmental goals are integral to almost every aspect of the Program. As such, these is no implementation plan for the environmental goals separate from the environment-relevant goals of the four Program implementation plans.

***Goal* – Reduce emissions in urban non-attainment areas**.

***Goal* – Reduce global greenhouse gas emissions**.

Relevant Strategic Objectives:

- Analyze and compare the full environmental benefits achievable using hydrogen energy. This should include thermochemical and electrolytic hydrogen production, and use of hydrogen both in the utility and transportation sectors

Hydrogen reduces emissions in urban non-attainment areas while reducing greenhouse gas emissions. A transition to hydrogen-fueled automobiles and other vehicles can virtually eliminate urban air pollution and reduce carbon dioxide emissions. This will occur either through using renewable energy sources, by producing hydrogen from natural gas using a means that does not produce CO_2 such as pyrolysis, or by sequestering carbon dioxide from fossil fuels used at central hydrogen production facilities. Initially, even the use of natural gas reduces the amount of pollution compared to the use of gasoline.

Major Activities and Accomplishments:

- Completed an analysis of the relative merits of various clean car alternatives including fuel cell vehicles (direct hydrogen, gasoline and methanol), hybrid electric vehicles (thermostat series hybrid, load following series hybrid and parallel hybrid with hydrogen, diesel fuel and natural gas fuels), a fuel cell range extender battery EV, and a fuel cell vehicle with a regenerative or reversible fuel cell system on the vehicle. The analysis compared the mass production cost, local emissions of criteria pollutants, greenhouse gas emissions and oil import impacts of each vehicle type. The direct hydrogen fuel cell vehicle provided the greatest reduction in environmental costs of all 14 vehicles evaluated, assuming that the hydrogen was produced from natural gas. If the hydrogen were produced by renewables, there would be obviously zero emissions of any type.

Significance of Results to Goals:

Hydrogen solutions will provide methods with a very broad applicability that can effect a wide range of options in the energy generation and transportation sectors. Fuel cell cars and natural gas/hydrogen vehicles were shown to be among the best options for consideration to reduce emissions in non-attainment areas in the transportation sector.

However, further analyses are necessary to assess the cost effectiveness of the approaches and the cost of carbon reductions per tonne of carbon dioxide removal. If a target less than $50/tonne of carbon dioxide removed is achieved then hydrogen can be considered with other technologies as an attractive economical solution.

2.4 Policy, Planning, and Analysis Goals

Planning and analysis is required to allow the Program to determine the technologies and systems that can best meet national strategic objectives in a cost-effective manner. Analysis is conducted for the Hydrogen Program at three levels: early awareness of potential options (through portfolio analysis), R&D program assessment (through technoeconomic analysis), and technology validation, (through market segment, time-dependent cost performance analysis, and private sector investment).

***Goal* – Ensure that Federal R&D investments in hydrogen production, storage, distribution, and end-use technologies will provide the maximum value added to national strategic goals including global greenhouse emission mitigation.**

Relevant Strategic Objective:

Prepare a portfolio analysis that (1) defines specific market criteria to guide R&D investment priorities for hydrogen as a competitive fuel in stationary and mobile applications in air quality non-attainment areas, and (2) defines strategic criteria to guide R&D investments to enhance global competitive leadership in hydrogen technology development. The portfolio analysis will help define an R&D investment strategy and portfolio management plan to allocate R&D resources over the next 5 years.

Major Activities and Accomplishments:

Major activities within this strategic objective include the following:

- Identify integrated transition strategies to sustainable hydrogen systems.
- Prepare scenario analyses.
- Conduct ongoing evaluation of key issues for the use of hydrogen in transportation. Included are analyses of home and distributed refueling systems, vehicle design, small-scale production units, and the coupling of carbonless electricity sources with hydrogen vehicles.
- Quantify the advantages of centralized versus distributed hydrogen generation including the use of carbon sequestration for the purpose of reducing atmospheric CO_2 concentrations.
- Identify opportunities for hydrogen in maritime, airplane, and locomotive applications.

Major accomplishments within this strategic objective:

- Determined that reversible fuel cells have high potential value in the case of refueling stations that generate hydrogen on-site.
- A transportation and storage study of the compared distributed versus centralized hydrogen distribution systems showed that the compression and storage of gaseous hydrogen at a distributed fueling station added about $2.21/MMBtu to the production cost of hydrogen, whereas the additional cost for liquefaction, transport and storage at the stations is approximately $6.2/MMBtu. Thus, the program is emphasizing on-site generation of hydrogen with the potential to include liquid hydrogen for long range applications.

***Goal* – Identify and evaluate key market segments and market entry conditions for hydrogen utilization in transportation and in electricity generation at distributed and remote locations.**

Relevant Strategic Objective:

- Characterize key market segments, by market size, end-use patterns, time-dependent cost/performance and other critical market entry criteria, consumer requirements and preferences, private sector investments and production requirements, government investments and incentives/regulations, competing fuels and technologies, and potential return on private and public investments. Define pathways. and transition strategies to attain a given share of these markets for hydrogen-fueled technologies. Identify and assess key technology development baselines for market entry and penetration.

Major Activities and Accomplishments:

Major activities within this strategic objective include the following:

- Characterize hydrogen fuel cell and storage systems that can successfully compete in electricity market.
- Characterize the advantages of hydrogen-based energy systems for off-grid energy systems, including an assessment of storage opportunities and fuel matching.
- Explore the opportunities for systems that combine heat, power, and hydrogen production in distributed and residential applications.
- Determine the necessary requirements for hydrogen storage in PV and wind energy systems.
- Explore opportunities for the coproduction of hydrogen and electricity to serve as refueling stations.
- Conduct technical and economic feasibility studies of projects proposed for technology validation under Hydrogen Program solicitations. This will include reviewing proposals and ongoing projects for economic feasibility, technical feasibility, marketing issues, teaming arrangements, and other elements including safety considerations, environmental impacts, and benefits to the U.S.
- An evaluation of infrastructure and fuel storage requirements indicated that PEM fuel cell electricity generation systems would need to operate on kerosene or diesel fuel in inland Alaska. Use of a fuel cell in individual homes or buildings would be able to utilize heating oil for both the production of electricity and heating. A 40% reduction in the amount of diesel fuel is required from the existing Alaskan scenario and the levelized cost of electricity is $0.15/kWh.
- An analysis demonstrated that the economics of stationary fuel cell systems can be enhanced substantially by generating excess hydrogen during the off-peak electrical periods, and using or selling that hydrogen for fuel cell vehicles. In essence the hydrogen is a high value product, and can be sold for higher cost per joule than electricity. Making hydrogen off-peak increases the capacity factor of the natural gas steam reformer, which contributes to the improved economics of the project relative to selling or providing only electricity from the fuel cell. The analysis indicated that hydrogen and electricity production from a $1,000/kW reformer PEM fuel cell system would be sold for $1.20/gallon equivalent gasoline and 5.7 cents/kWh.

- Reviewed eight proposals submitted to the Hydrogen Program for Phase II funding under the 1997 solicitation. The reports were reviewed for economic feasibility, technical feasibility, marketing issues, teaming arrangements, and other elements including safety considerations, environmental impacts, and benefits to the U.S. A detailed economic analysis was performed for each of the eight proposals, covering such diverse technologies as biomass gasification, fuel cells, and vehicle applications.

Relevant Strategic Objective:

- Perform technical and economic analyses on hydrogen integrated pathways in order to ascertain the proper routes to hydrogen implementation.

Major activities within this strategic objective include the following:

- Conduct technoeconomic analyses on all research projects funded by the Program. This will include research in the following areas: hydrogen from biomass, electrolytical and photoelectrochemical hydrogen production, hydrogen from fossil fuels, and hydrogen from biological processes.
- Characterize hydrogen storage options, with a focus on onboard compatibility with PEM fuel cells and hydrogen fueling infrastructure applications.
- Provide guidance to researchers such that work focuses on areas that most strongly affect the cost of the final product and help update Program R&D Roadmaps as research advances are achieved.
- Quantify environmental benefits of hydrogen as it meets national strategic goals, including greenhouse gas emissions, urban air quality, and energy security.

Major accomplishments within this strategic objective:

- Determined the economic feasibility of a fiber optic hydrogen detector that is being researched in the Hydrogen Program. The sensor was found to have excellent potential, and the determination that the light source was a large contributor to the overall cost led researchers to examine alternatives. The initial cost estimate showed the light source to be 27.4 to 58.9% of the overall detector system cost in all scenarios studied. Using the new light source, the total system costs for the 4 scenarios studied (6 sensors/vehicle and 20 sensors/vehicle for a production rate of 5,000 vehicles/year and for 3 million vehicles/year) ranged from $4.30/detector to $13.18/detector and $33.20/vehicle to $150.80/vehicle. These costs are much lower than the cost of existing hydrogen sensing devices — ranging from $27 to 3,900 sensor before the addition of parts required for the integrated system.
- Performed an assessment of hydrogen production via electrolysis of hydrogen bromine showing that the full life cycle fuel and electricity requirements are high compared to steam methane reforming. This result has focused the Hydrogen Program's R&D efforts in the area of HBr systems on electricity storage.
- Studied the technical and economic feasibility of producing hydrogen from PV/electrolysis, wind/electrolysis and photoelectrochemical (PEC) systems. Hydrogen production by direct conversion of sunlight by photoelectrochemical devices was found to have economic potential, with the projected *production* cost of hydrogen being about $19/MMBtu in the near term, and about $9.5/MMBtu in the mid- to long-term (in 2010). If research goals on efficiency and stability can be met, the selling price of the product hydrogen will be less than that projected from direct PV/electrolysis systems. This study also found that coupling PV and wind electrolysis systems with the grid significantly improves the economics of producing hydrogen

from sunlight and wind, thus identifying opportunities to reduce hydrogen costs and moving hydrogen into commercial systems.

- The technical and economic viability of producing hydrogen from biomass by four different systems was studied. The analysis, which examined biomass gasification, biomass pyrolysis, and biomass partial oxidation, showed that there are definite opportunities for biomass to contribute a significant amount to future hydrogen needs. In particular, an indirect low-pressure biomass gasification system can produce hydrogen for less than $2/kg ($13.3/MMBtu) for reasonable feedstock prices and less than $7.6/MMBtu for the biomass pyrolysis system with the production of coproducts and the use of agricultural residues.

***Goal* – Develop and apply metrics to measure the Program's contribution to attaining national strategic energy goals and market share in key market segments.**

Relevant Strategic Objectives:

- Develop a programmatic database that includes metrics to measure the Program's contribution to the attainment of national strategic objectives and market share in key market segments. The database will incorporate data on cost, performance, reliability, lifetime, and other key characteristics for hydrogen technologies to contribute to national strategic energy objectives and compete in key market segments.

The database will incorporate data on cost, performance, reliability, lifetime, and other key characteristics for hydrogen technologies to contribute to national strategic energy objectives and compete in key market segments.

Major activities within this strategic objective include the following:

- Analysis work to give an overall picture of the position of the R&D portfolio relative to market entry conditions and national strategic energy objectives. For each production, storage, and end-use pathway, the cost, performance, reliability, and market condition criteria are developed by coordinating analysis work performed under the previous strategic objectives.
- Determination of metrics for use in analyses performed for the Hydrogen Program such as: cost goals for R&D efforts, minimum conversion efficiencies, credits for reduced CO_2 emissions, market capture targets, and safety criteria.

Major accomplishments within this strategic objective:

- Created a consistent set of long-term renewable energy cost and performance projections, in addition to utility cost and rate forecasts.
- Determined the cost goals for several renewable hydrogen systems.

2.5 Outreach and Coordination Goals

The Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 mandates that DOE develop and implement hydrogen energy. In 1996, the Hydrogen Future Act established a DOE role in increasing industrial participation in developing and disseminating information pertaining to hydrogen energy systems. Each of these pieces of legislation contained specific calls for active technology transfer and outreach programs

Outreach is crucial to the DOE Hydrogen Program in order to address non-technical barriers such as codes and standards for infrastructure implementation and public safety concerns. Outreach is also imperative to promote and educate the public, decision-makers, and business leaders about opportunities and progress towards the establishment of an energy infrastructure with hydrogen as a clean, safe fuel.

***Goal:* Develop informed constituencies in the industrial and public sectors as part of a strategy to accelerate the commercialization of renewable hydrogen technologies.**

***Relevant Strategic Objectives*:**

- Develop a Five Year Outreach Plan that integrates public, industry, and educational outreach activities that together will improve understanding of the pivotal role hydrogen will play in creating a sustainable energy, economic, and environmental future.
- Identify the key constituencies that must be better informed about hydrogen and prepare the materials and tools needed to inform these constituencies.
- Coordinate Program efforts with other DOE offices and other government agencies. Be cognizant of efforts of state and local governments as well as foreign interests. Work with private industry and the NHA.

Major Activities and Accomplishments:

The Program structures its outreach and coordination in terms of four areas, namely, communication, barrier resolution, education, and awareness.

Communication

- Prepared Five Year Outreach Plan for DOE Hydrogen Program.
- Held Outreach Workshops with decision-makers in key targeted industries to inform them about the DOE Hydrogen Program and to understand their interests and concerns about hydrogen energy. Implementing Hydrogen Energy Systems: Industry and Government Partnerships. Held Industry Outreach meetings with 26 companies.
- Provided information to decision-makers on a regular basis to keep them updated about hydrogen energy activities.
- Held Annual Technical Workshops to solicit opinions and to provide an opportunity for programmatic inputs on selected topics. For example, DOE held a PEM fuel cell workshop in cooperation with the Fuel Cells ‘97 Review Meeting in August 1997.

Barrier Resolution

- Assisted the National Renewable Energy Laboratory in producing the Codes and Standards Sourcebook which is a detailed effort to list all relevant codes and standards in the U.S. and Canada (e.g., IEEE, ASME, ISO, EIC, ANSI). This book is designed to provide information to project managers on designing, building, and operating safe hydrogen projects. The information presented is for technology developers and code officials. The Canadian Hydrogen Association is compiling codes and standards information from Canada. This Sourcebook will be available in book form and as a CD-ROM.
- Promoted the development of codes and standards for hydrogen by being an important participant with the International Standard Organization. The International Standard Organization for Hydrogen Technologies (ISO/TC 197) is supported by DOE and the National Hydrogen Association. Examples of standards that are being developed by this group include: Hydrogen Fuel-Product Specification; Airport Hydrogen Fueling Facility; and Basic Requirements for Safety of Hydrogen Systems.

Education

- Established three Centers of Excellence at the University of Hawaii, Florida Solar Energy Center and the University of Miami. Each university will have areas of technical competence that is pertinent to the Hydrogen Program. Graduate students will be provided fellowships to pursue their dissertations in relevant subject areas.
- Developed an interactive Mission H2 CD-ROM Project about hydrogen energy targeted at middle school students. Tested the CD-ROM at several schools and forums on different age audiences (e.g., middle school, elementary school).
- Held the Secondary School Invitational and several other educational seminars. A high school program was organized to teach students that science is fun. The main feature of the program was the "Dr. Bob Show" where hands-on chemistry experiments using such objects as liquid nitrogen, dry ice, and neon lights reinforce the chemical properties of hydrogen. A panel of speakers promoting careers in science and engineering called *Career Opportunity of a Lifetime (COOL),* made up of practitioners/former students and current students in the field was assembled at the meeting.
- Produced a variety of materials were also for the second annual Secondary School Invitational at the U.S. Hydrogen Meeting, such as color brochures, stickers, presentations and awards. Student handouts containing hydrogen-related information were prepared and distributed in a folder together with the program agenda. Students also received a personal certificate of award, acknowledged by the U.S. Department of Energy, to recognize their participation in the program.

Awareness

- Researched international hydrogen energy demonstration projects to prepare an informational brochure that is non-technical and geared towards the general public.
- Supported the publication of The Hydrogen and Fuel Cell Letter which is a monthly newsletter that focuses on U.S. and international progress dealing with fuel cells and hydrogen. The letter is distributed to a wide segment of the industrial community.
- Supported the development of a documentary: *Element One. Hydrogen: Key to the Sustainable Energy Revolution,* a one-hour documentary funded by private and public sector, including DOE.

- Developed an agenda to address programmatic strategies for expanding activities of the National Hydrogen Program by holding a Hydrogen Consensus Meeting.
- Compiled a summary of hydrogen websites as an adjunct to the maintenance and updating of the Hydrogen InfoNet website.
- Prepared State Write-ups on projects funded by the DOE Office of Energy Efficiency and Renewable Energy - Approximately 43 write-ups on projects funded by the Hydrogen Program were compiled.
- Established the National Renewable Energy Laboratory hydrogen energy website.
- Prepared Technology Validation Projects Fact Sheets to publicize some of the newer technology validation projects. One-page fact sheets were written and produced for each of the industry cost-shared partnerships within the DOE Hydrogen Program.

Interdepartmental and Interagency Coordination

- Within Energy Efficiency and Renewable Energy, a special assistant to the Assistant Secretary was given the responsibility for coordinating and integrating the activities associated with the Proton Exchange Membrane fuel cell among the different sectors of Energy Efficiency and Renewable energy. A workshop was held in October 14, 1997 with industry representing the transportation, electric generation and industry sectors. They provided the Department with a set program goals and milestones. The sectors have developed an integrated fuel cell program that compliments one another's efforts and plans collaborative activities including a coordination of fuel reformer, fuel cell research and development and technology validation projects.
- Several workshops were conducted between the Office of Fossil Energy and the Hydrogen Program to establish programs that need to be co-managed and co-funded as recommended by the President's Committee for Advance Science and Technology (PCAST). Work statements were generated for cofunded and collaborative activities concerning the production of hydrogen from low Btu coal and an advanced research Program Research and Development Announcement for carbon dioxide capture, enabling science for the hydrogen economy and fuels for the future.
- Meetings with the Office of Energy Research (OER) have led to several steps to co-manage and co-fund programs as also recommended by PCAST. OER has provided scientists to be reviewers of long-term research and development programs during the hydrogen program annual review. On the basis of their review long-term high risk projects in photoelectrochemical, photobiological and storage activities will be more collaboratively managed.
- The National Aeronautics and Space Administration has held three workshops on future programs and activities. The Hydrogen Program is a participant in coordinating hydrogen production and storage programs for consideration with the hydrogen airplane. A Memorandum of Understanding describing the roles of the two agencies will be developed.

Relevance of Accomplishments to Implementation Plan:

Significance of Results to Goals:

It is critical that hydrogen technologies be shown to the public as achievable, cost-effective, convenient, and safe. Effectively communicating the positive attributes of hydrogen, along with addressing concerns regarding the cost, safety, and flexibility of hydrogen, will be important to enhance the transition of hydrogen into a clean and sustainable energy source. It is also important to educate and train an energy workforce and to promote market conditioning of hydrogen energy. A proactive approach to accomplish these objectives can enhance the transition to clean, sustainable energy.

The progress being made in the core research and development, and technology validation programs add further emphasis to the need for an effective outreach and coordination activity. New technological products will come into being and new integrated system concepts will be demonstrated that users and the public will need to be aware of to make informed decisions.

As examples, three integrated system concepts that need greater public awareness are:

- A natural gas/hydrogen driven car especially equipped to maintain the high-level of performance expected from a high-use sedan that produces only trace amounts of emissions.
- Hydrogen fuel cell cogeneration systems that produce heat and power on the premises. Industry is moving aggressively in this direction with small, dishwasher-size appliances.
- Onboard storage of hydrogen. The industry is considering a gasoline car with on-board reforming of hydrogen. It is more efficient, less costly, and cleaner to store hydrogen on the vehicle. However, this adaptation requires storage systems and infrastructure to support these vehicles. Onboard reformers will necessarily cost more than stationary reformers per unit of hydrogen delivered since they suffer from diseconomics of scale and low capitalization rates. The co-production of hydrogen and electricity can be a means to further establish an efficient infrastructure and lower the cost of hydrogen and electricity.

The development of codes and standards need to be kept apace with validation programs, and effective hydrogen safety and handling procedures need to be disseminated to local and State policy makers. Program progress needs to be revealed to industry decision makers through workshops to ensure their implementation in mainstream transportation and utility systems.