Hydrogen Posture Plan

An Integrated Research, Development, and Demonstration Plan

February 2004

United States Department of Energy

A National Commitment

In his State of the Union address, President Bush announced a $1.2 billion hydrogen initiative to reverse America's growing dependence on foreign oil and reduce greenhouse gas emissions. The President urged the development of commercially viable hydrogen fuels and technologies for cars, trucks, homes, and businesses.

> *With a new national commitment, our scientists and engineers will overcome obstacles…so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy.*

— President Bush,
State of the Union Address,
January 28, 2003

In submitting his budget request for fiscal year 2004, Energy Secretary Spencer Abraham responded to the President's call by outlining a key role for the U.S. Department of Energy in coordinating this multi-faceted technology development effort:

> *Government coordination of this huge undertaking will help resolve one of the difficulties associated with the development of a commercially viable hydrogen fuel-cell vehicle:…Which comes first, the vehicle or the infrastructure of manufacturing plants, distribution and storage networks, and the convenient service stations needed to support it?…[The Department will work with all stakeholders] to develop both the vehicle and the infrastructure in parallel—and by so doing, advance a commercialization decision by 15 years, from 2030 to 2015.*

— Energy Secretary Abraham,
2004 DOE Budget Submission
February 3, 2003

The National Academies' report on the DOE hydrogen program concludes that:

> *A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy resources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants.*

— The National Academies
Committee on Alternatives and Strategies for
Future Hydrogen Production and Use
February 2004

This document describes the Department's plan for successfully integrating and implementing technology research, development, and demonstration activities needed to cost-effectively produce, store, and distribute hydrogen for use in fuel cell vehicles and electricity generation.

DOE's Integrated Plan for Action

Energy is the life-blood of our Nation. It is the mainstay of our standard of living, economy, and national security.

In the United States demand for oil is projected to increase by nearly 50 percent by 2025. Petroleum imports already supply more than 55 percent of U.S. domestic needs, and those imports are projected to increase to more than 68 percent by 2025. Our growing dependence on foreign sources of energy threatens our national security. As a Nation, we must work to reduce our dependence on foreign sources of energy in a manner that is affordable and preserves environmental quality.

Vision for the Hydrogen Economy

Hydrogen is America's clean energy choice.

Hydrogen is flexible, affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country.

A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond, February 2002.

Clean forms of energy are needed to support sustainable global economic growth while mitigating impacts on air quality and the potential effects of greenhouse gas emissions. To address these challenges, the President's *National Energy Policy* and the U.S. Department of Energy's (DOE's) Strategic Plan call for expanding the development of diverse domestic energy supplies. The President has proposed $1.2 billion over the next five years to support a new Hydrogen Fuel Initiative. The Initiative will accelerate the pace of research and development on the hydrogen production and distribution infrastructure needed to support hydrogen-powered fuel cells for use in transportation. It will also address the need for appropriate safety codes and equipment standards and for improved public education on hydrogen as an energy carrier.

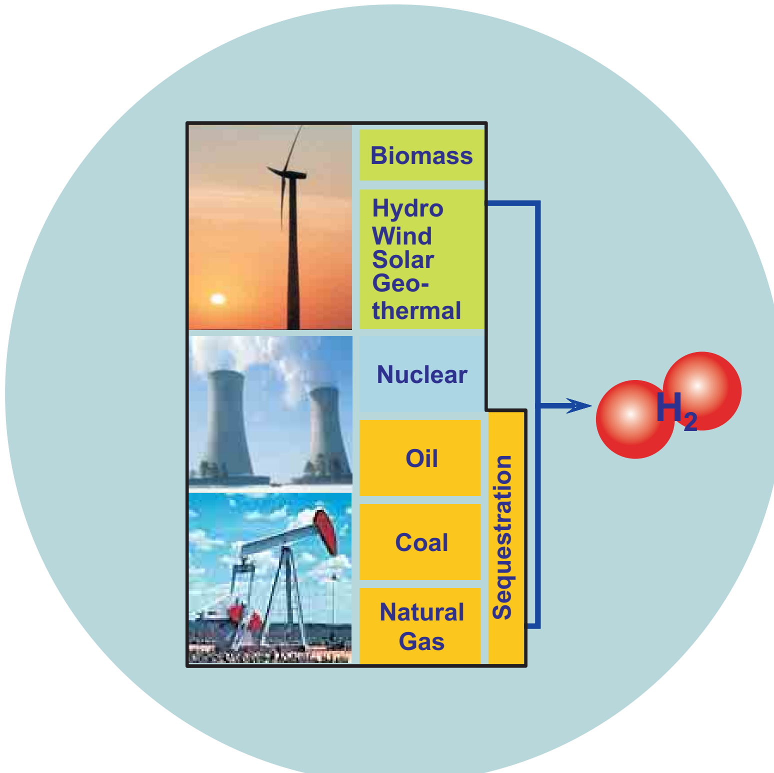
Working with industry, the Department developed a long-term national vision for moving toward a hydrogen economy—a solution that holds the potential to provide virtually limitless clean, safe, secure, affordable, and reliable energy from domestic resources. To realize this vision, the Nation must develop and demonstrate advanced hydrogen fuel cell and infrastructure technologies while continuing to promote complementary near-term energy efficiency and renewable energy solutions. Toward this end, the Department has worked with public and private organizations from across the country to develop a *National Hydrogen Energy Technology Roadmap*. The Roadmap identifies the technological research, development, and demonstration steps required to make a successful transition to a hydrogen economy. The Roadmap stresses the need for parallel development of model building codes and equipment standards to enable technology integration into commercial energy systems, and outreach programs to effectively educate local government officials and the public, who will determine the long-term acceptance of these technologies.

DOE Promotes Hybrid Vehicles as its Near-term Strategy

Hydrogen has the long-term potential to reduce our dependence on foreign oil and lower our carbon and criteria emissions from the transportation sector. In the next two decades, conservation and increased efficiency through the use of gasoline-electric hybrid vehicles are the best options for reducing oil use and emissions. DOE provides over $90 million annually for development of hybrid vehicle components for light-duty applications. In addition, the Federal government offers a $1,500 tax deduction for qualifying hybrid vehicles purchased in 2004. Also, many states are taking actions (such as waiving sales tax) to promote hybrid vehicles.

This *Hydrogen Posture Plan* describes how DOE will integrate its ongoing and future hydrogen R&D activities into a focused Hydrogen Program. The program will integrate technology for hydrogen production (from fossil, nuclear, and renewable resources); infrastructure development (including delivery and storage); and fuel cells for stationary and transportation applications. A coordinated DOE Hydrogen Program will improve the effectiveness and accountability of DOE's research, development, and demonstration (RD&D) activities and strengthen its contribution to achieving the technical milestones on the road to a hydrogen economy.

Domestic Hydrogen Production Options



...the first car driven by a child born today could be powered by hydrogen, and pollution-free.

— President Bush,
State of the Union Address,
January 28, 2003

Executive Summary

The *Hydrogen Posture Plan* was prepared by the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) in response to a directive by Energy Secretary Spencer Abraham. As directed, EERE developed the Plan with the support of the DOE Offices of Fossil Energy, Science, and Nuclear Energy, Science and Technology to outline the activities, milestones, and deliverables that the Department plans to pursue to support America's shift to a hydrogen-based energy system. The *Hydrogen Posture Plan* integrates the Department's planning and budgeting for program activities that will help turn the concept of a hydrogen-based economy into reality. More specifically, this Plan outlines the Department's role in hydrogen energy research and development in accordance with the *National Hydrogen Energy Roadmap* released by Secretary Abraham on November 12, 2002, and lays the foundation for a coordinated response to the President's goal for accelerated research on critical path hydrogen fuel cell and infrastructure technologies.

Key Points

- Use of hydrogen as an energy carrier can enhance long-term energy security while mitigating the effects of air pollution and greenhouse gas emissions. The *National Hydrogen Vision*, developed in response to the President's *National Energy Policy*, envisions hydrogen as a flexible, safe, affordable, domestic energy resource used in all sectors of the economy and all regions of the country. Hydrogen will become America's "clean energy choice," joining electricity as a primary energy carrier and providing the foundation for a globally sustainable energy system.

- Technical challenges to achieving a hydrogen economy include lowering the cost of hydrogen production, delivery, storage, conversion, and end-use applications. Additional needs include effective building codes and equipment standards to address safety issues as well as outreach and education campaigns to raise awareness, accelerate technology transfer, and increase public understanding of hydrogen energy systems. These challenges and the general paths forward are discussed in detail in the *National Hydrogen Energy Roadmap*.

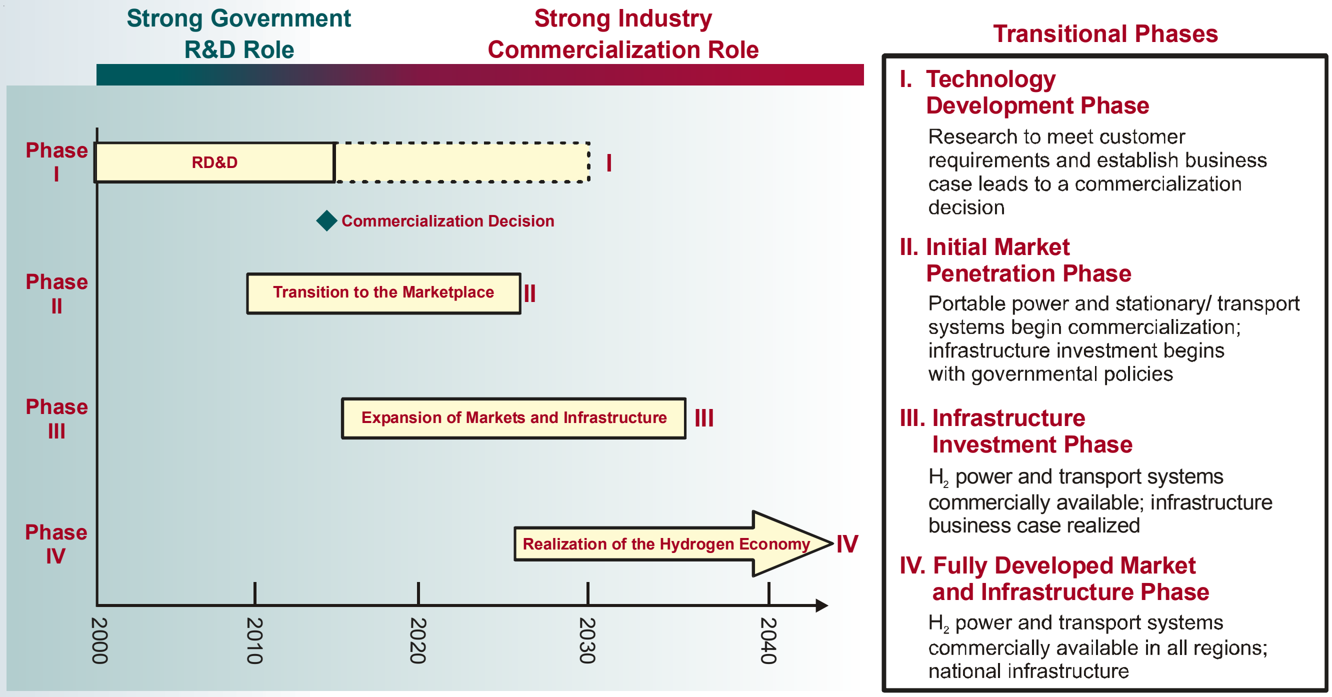
> *"This committee believes that investigating and conducting RD&D activities to determine whether a hydrogen economy might be realized are important to the nation."*
>
> — The National Academies
> Committee on Alternatives and Strategies for
> Future Hydrogen Production and Use
> February 2004

- The *Hydrogen Posture Plan* integrates existing and future activities by DOE to pursue the R&D priorities laid out in the Roadmap and overcome the related technical challenges. DOE and other agencies of the Federal government will have to play a leadership role in the transition to a hydrogen economy. DOE envisions a four-phase process to fully realize a hydrogen economy by 2030-2040, as shown in the figure on the following page.

- Because the research is not guaranteed to be successful and better options could arise for addressing foreign oil dependency and carbon emissions in the transportation sector, a commercialization decision precedes the infrastructure investment phase.

- The Federal government will play a key role in the near term, while technologies are being developed and demonstrated in limited markets. If the research is successful in

Government-Industry Roles in the Transition to a Hydrogen Economy



The timeframe is long and the investment is large to develop a hydrogen and transportation market that reduces our Nation's dependence on foreign sources of energy while minimizing environmental impacts.

the mid term, the Federal government will become an early technology adopter, enacting policies that will nurture the development of an industry capable of delivering significant quantities of hydrogen to the market place. Industry's role will become increasingly dominant in the mid- to late- stages.

✦ The Department's mission is to assist in developing and demonstrating technologies for producing, storing, and delivering hydrogen in an efficient, clean, safe, reliable, and affordable manner. Some of these activities directly contribute to the development of a hydrogen economy, such as those aimed at hydrogen production, storage, and development of direct hydrogen fuel cells for transportation applications. Related DOE efforts that also contribute to achieving a hydrogen economy include the development of high-temperature fuel cells for stationary applications and carbon sequestration technologies.

✦ Key program milestones for achieving a hydrogen economy include the following:
- On-board hydrogen storage systems with a 9% capacity by weight to enable a 300 mile driving range.
- Hydrogen production from natural gas or liquid fuels at a price equivalent to $1.50 per gallon of gasoline at the pump, untaxed, no carbon sequestration, at 5,000 psi.
- Polymer electrolyte-membrane automotive fuel cells that cost $30-45 per kilowatt and deliver 5,000 hours of service (service life of vehicle).
- Zero emission coal plants that produce hydrogen and power with carbon capture and sequestration at $0.80 per gallon of gasoline equivalent (gge) at the plant gate ($1.80/gge delivered).
- Hydrogen production from wind-based electrolysis approaching $2.00 per gallon of gasoline equivalent untaxed (using wind electricity at $0.04 per kwh), delivered at 5,000 psi.
- Hydrogen fuel delivery technologies that cost $1.00 per gallon of gasoline equivalent.

Next Steps

- Coordinate the detailed multi-year RD&D plans and priorities for hydrogen and related technology development efforts in the Department to make them consistent with this planning document and the National Academies' study requested by DOE.

- To strengthen coordination within DOE, establish a working group composed of representatives from the Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy, Science and Technology; Science; Management, Budget, Evaluation/CFO; and Policy and International Affairs (in an oversight capacity). This working group should meet periodically to perform the following functions:
  - Evaluate the Department's progress in meeting milestones and performance goals in hydrogen and related activities.
  - Strengthen information exchange on technical developments.
  - Help ensure continued close integration among the Department's hydrogen-related activities (e.g., budgeting, execution, evaluation, and reporting).
  - Provide suggestions for improving management and technical performance.
  - Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways.

- Prepare a Program Management and Operations Plan to provide further detail on the overall management and integration of the Department's Hydrogen Program, including reporting requirements, oversight/advisory roles and responsibilities, and baseline requirements, cost, and schedule.

- Reflect the importance of the following activities in the Department's out-year planning and budgeting:

  - Exploratory research in hydrogen storage, production, and fuel cell cost and durability.
  - Hydrogen delivery and development of infrastructure (these activities need to be closely coordinated with the Department of Transportation (DOT), which is responsible for efforts to ensure the safety of the hydrogen delivery system).
  - Economic and systems analyses for determining and mitigating investment risks associated with hydrogen infrastructure and related technologies (e.g., fuel cell systems engineering and manufacturing plants).

- Increase the energy industry participation in the initiative, in recognition of the industry's key role in energy production and delivery infrastructures. Greater energy and utility industry participation is vital to a successful transition to a hydrogen economy.

- Strengthen and continue existing interagency coordination efforts to ensure that Federal investments in hydrogen energy development are leveraged to the maximum extent. The following agencies are participating with the Department of Energy in the Hydrogen Interagency Research and Development Task Force to discuss national hydrogen and related activities: Departments of Defense, Commerce, Transportation, Agriculture, and State; Office of Management and Budget; Office of Science and Technology Policy; National Science Foundation; National Institutes of Standards and Technology; Environmental Protection Agency; and National Aeronautics and Space Administration.

- Strengthen international cooperation on hydrogen-related research, development, and demonstration programs and on the development of interoperable codes and standards through the International Partnership for the Hydrogen Economy.
- Be aware of the nation's regulatory framework of energy, economic, and environmental policies at the federal, state, and local levels, and work with the appropriate agencies to coordinate the timing of policy instruments and regulatory actions to allow technology to meet market requirements.

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1. Introduction

Today, America is confronted by major energy challenges:

- Attaining greater energy and economic security by reducing dependence on foreign energy supplies,
- Increasing affordable domestic energy supplies to meet anticipated demand, and
- Reducing air pollution and addressing concerns about climate change.

The Administration's *National Energy Policy (NEP)* and the U.S. Department of Energy's (DOE's) Strategic Plan both call for reducing U.S. reliance on imported oil. The NEP also acknowledges the need to increase energy supplies and use more energy-efficient technologies and practices. As highlighted in the NEP, energy-related activities are the primary source of air pollution and greenhouse gas emissions. The need for clean, abundant, affordable, domestically produced energy has never been greater.

As President Bush acknowledged in his January, 2003, State of the Union address, hydrogen has the potential to play a major role in America's future energy system. DOE recognizes that the development of this abundant element as an "energy carrier" will help address national concerns about energy supply, security, and environmental protection.

Hydrogen can be derived from a variety of domestically available energy sources (see several example pathways in Appendix A). It has a wide variety of applications, including fuel for automobiles and distributed and central electricity and thermal energy generation.

The Department also recognizes that the attainment of a "hydrogen economy" will require a coordinated national effort and sustained activities by diverse public and private stakeholders. Today hydrogen is commonly used in industrial applications to manufacture petrochemicals and fertilizers. The existing hydrogen production and distribution infrastructure is insufficient, however, to support widespread use of hydrogen for energy. With the exception of aerospace and rocket propulsion applications, the current hydrogen industry does not produce hydrogen as an energy carrier or as a fuel for energy generation, except for pilot-scale R&D projects. Taking this step will require research, development, and demonstrations to improve performance and lower costs for hydrogen production, delivery, storage, conversion, and end-use applications, and activities to provide education and experience to safety and code officials. The President's proposed $1.2 billion Hydrogen Fuel Initiative will accelerate R&D funding in each of these areas.

Positive Attributes of Hydrogen as an Energy Carrier

Addresses national energy security, air quality, and greenhouse gas emissions:

- Can be derived from diverse domestic resources (fossil, nuclear, renewable)
- Compatible with high-efficiency fuel cells, combustion turbines and reciprocating engines to produce power with near-zero emissions of criteria pollutants
- Produces near-zero emissions of greenhouse gases from renewable and nuclear sources (sequestration needed for fossil-based hydrogen)
- Can serve all sectors of the economy (transportation, power, industrial, and buildings)

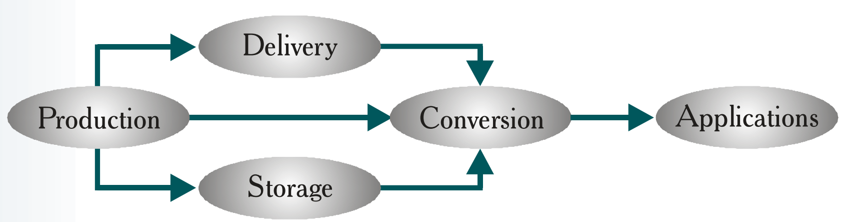
As a first step, the Department oversaw a National Hydrogen Vision and Roadmap process and incorporated the opinions and viewpoints of a broad cross-section of stakeholders in two key documents: *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, and the *National Hydrogen Energy Roadmap*.[1]

"Critical Path" Technologies Necessary for Developing a Hydrogen Economy

- Lower cost of producing and delivering hydrogen
- More compact, light weight, lower cost, safe and efficient storage systems
- Lower cost materials for advanced conversion technologies, especially fuel cells
- More effective and lower cost carbon-capture and sequestration processes
- Designs and materials that maximize the safety of hydrogen use

This document, the U.S. Department of Energy's *Hydrogen Posture Plan*, has been prepared to outline the activities, milestones, and deliverables that the Department must pursue to promote America's shift to a hydrogen-based energy system, the key elements of which are shown in Figure 1, below. Among the topics addressed are the schedules for evaluating and developing technologies to: a) produce and deliver hydrogen using various domestic resources (e.g., natural gas and coal using capture and sequestration of carbon dioxide; renewables including wind, solar, and biomass; and nuclear energy); b) store hydrogen; c) convert hydrogen to useful energy through advanced fuel cells and other devices; d) conduct limited "learning" demonstrations to measure technology progress; e) address education needs; and; f) develop and verify appropriate codes and standards for a variety of applications. The Posture Plan also addresses the critical role of developing a viable hydrogen infrastructure in achieving a successful FreedomCAR Partnership, a government-industry initiative for the advancement of high-efficiency hydrogen-powered fuel cell vehicles; and the important role of government policies in overcoming economic and institutional barriers to the development of a hydrogen infrastructure.

FIGURE 1. ELEMENTS OF A HYDROGEN ENERGY INFRASTRUCTURE



Production
- The production of hydrogen from fossil fuels, biomass, or water
- Involves thermal, electrolytic, and photolytic processes

Delivery
- The distribution of hydrogen from production and storage sites
- Involves pipelines, trucks, rail and barges
- Involves efficient reversible solid or liquid carrier systems

Storage
- The confinement of hydrogen for delivery, conversion, and use
- Involves tanks for both gases and liquids at ambient and high pressures
- Involves reversible and irreversible solid- and liquid-state systems, including metal and chemical hydrides

Conversion
- The making of electricity and/or thermal energy
- Involves combustion turbines, reciprocating engines, and fuel cells

End-Use Energy Applications
- The use of hydrogen for transportation systems such as fuel-cell vehicles, internal combustion engines, and for portable power devices
- The use of hydrogen for stationary energy generation systems, including distributed energy systems, central generating stations, and combined heat and power applications
- Involves performance and safety evaluations and development of codes/standards

[1] These documents can be found on the internet at www.eere.energy.gov/hydrogenandfuelcells

2. Key Drivers for a Hydrogen-Based Energy System

Three major factors compel us to consider new approaches to the way the United States produces, delivers, and uses energy. These drivers are

- Energy security
- Environmental quality, and
- International competitiveness

Energy Security

The United States must expand its domestic supply of energy. America's transportation sector relies almost exclusively on refined petroleum products. As shown in Figure 2, close to one-half of the petroleum consumed for transportation in the United States is imported, and that percentage is expected to rise steadily for the foreseeable future. On a global scale, petroleum supplies will be in increasingly higher demand as highly populated developing countries expand their economies and become more energy intensive. Hydrogen-powered fuel cell vehicles would not be dependent on foreign oil, since the hydrogen can be produced almost entirely from diverse domestic sources of fossil fuel, renewable, and nuclear energy. Its use as a major energy carrier would also provide the United States with a more efficient and diversified energy infrastructure, with a variety of options for fueling central and distributed electric power generation systems.

Fuel Cells Offer Large Improvements in Energy Efficiency and Emissions

Fuel cells represent a radically different approach to energy conversion, one that could replace conventional power generation technologies like engines and turbines in applications such as automobiles and small power plants. Fuel cells, like batteries, directly convert chemical energy into electric power, without the intermediate production of mechanical work. But unlike batteries, fuel cells do not need recharging; instead they use fuel to produce power as long as the fuel is supplied. Fuel cells operate quietly and are relatively compact. Largely because of these characteristics, hydrogen-powered fuel cells promise:

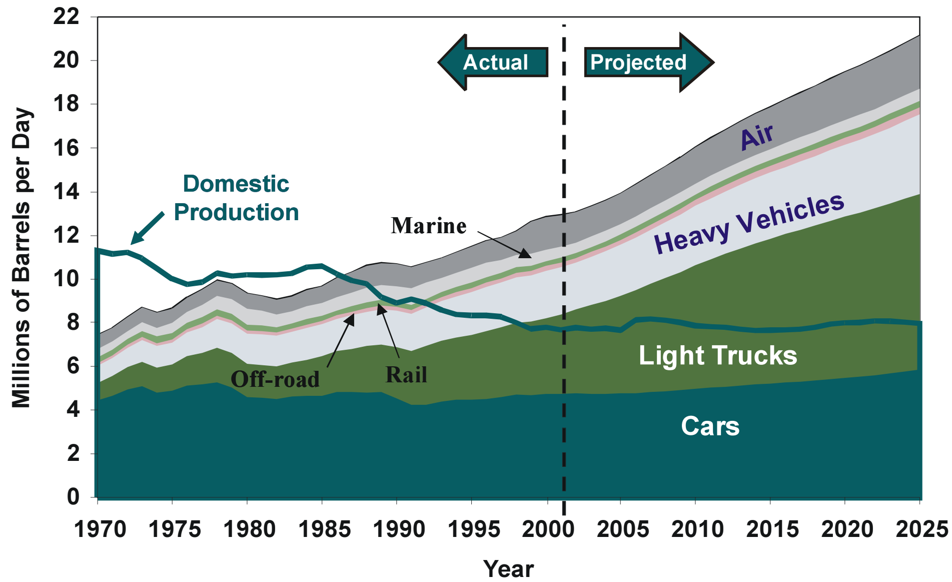
- For vehicles, over 50% reduction in fuel consumption compared to a conventional vehicle with a gasoline internal combustion engine
- Increased reliability of the electric power transmission grid by reducing system loads and bottlenecks
- Increased co-generation of energy in combined heat and power applications for buildings
- Zero- to near-zero levels of harmful emissions from vehicles and power plants

Environmental Quality

Air quality is a major national concern. It has been estimated that 60% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment. As shown in Figure 3, personal vehicles and electric power plants are significant contributors to the nation's air quality problems. Most states are now developing strategies for reaching national ambient air quality goals and bringing their major metropolitan areas into attainment with the requirements of the Clean Air Act. The introduction of hydrogen-based commercial bus fleets is one of the approaches that states are considering to improve air quality.

The combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions (chiefly carbon dioxide, CO_2) released into the atmosphere. The largest sources of CO_2 emissions are the electric utility and transportation sectors, as shown in Figure 3. Hydrogen can play an important role in a low-carbon global economy.

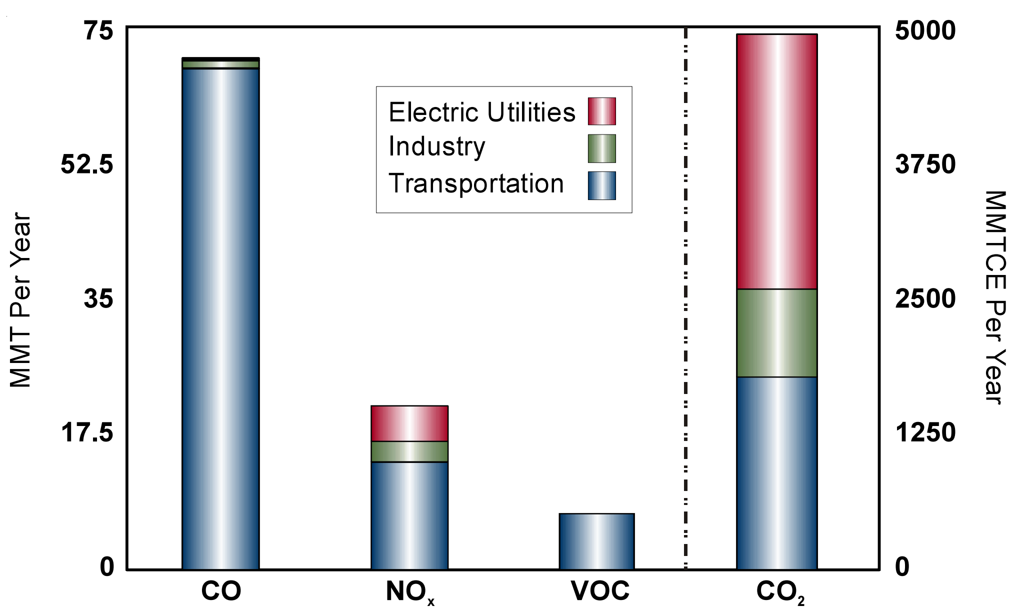
Figure 2. Growing U.S. Transportation Oil Gap



Source: Transportation Energy Data Book: Edition 22, September 2002, and
EIA Annual Energy Outlook 2003, January 2003.

To reduce carbon emissions, hydrogen production from coal, natural gas, and oil with the capture and sequestration of carbon can provide a way for domestic fossil fuels to remain viable energy resources. Fuel cells operating on hydrogen produced and distributed solely from renewable resources or nuclear energy result in near-zero carbon emissions.

Figure 3. Emissions from Fossil Fuel Combustion



Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000, *EPA-430-R-02-003, April 2002.*

It is clear that there is growing worldwide interest in hydrogen and fuel cell technology, as reflected in the dramatic increase in public and private spending since the mid-1990s in the U.S. and other countries. The U.S. government spends about $300 million annually on hydrogen and fuel cell programs, more than any other country in the world. A subset of these programs - - those that can directly contribute to the President's vision of commercially-viable hydrogen fuel cell vehicles by 2015 - - comprise the Hydrogen Fuel Initiative. These programs have already begun to see significant funding increases as part of the President's commitment to request $1.2 billion over five years for these activities. In addition, private sector spending on these activities in the U.S. is generally greater than in other countries. Thus, the U.S. is clearly a leader. Other countries are increasing investment as well. In 2003, the Japanese government nearly doubled its fuel cell R&D budget to $268 million, from $184 million in 2002. In April 2003 Japan launched a joint government/industry demonstration of hydrogen fuel cell vehicles, including the deployment of more than seven new hydrogen refueling stations.[2] Governments and companies in Canada, Europe, and Asia are also investing heavily in hydrogen research, development and demonstration. For example, 10 new hydrogen refueling stations will be built in Europe over the next few years to fuel hydrogen-powered buses.

International Partnership for the Hydrogen Economy: Membership

Australia	India
Brazil	Italy
Canada	Japan
China	Norway
European Community	Republic of Korea
France	Russia
Germany	United Kingdom
Iceland	United States

The economic stakes are high – a recent report by PricewaterhouseCoopers projects global demand for all fuel cell products (in portable, stationary, and transportation power applications) to reach $46 billion per year by 2011 and to grow to more than $2.5 trillion per year in 2021.[3] The United States should strive to continue to be a global leader in hydrogen and fuel cell technology development and commercialization. To foster cooperation, Secretary of Energy Spencer Abraham called for an "International Partnership for the Hydrogen Economy" at the International Energy Agency Ministerial meeting in April 2003.

The partnership provides a mechanism to organize, evaluate and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy. Ministers from the sixteen members of the International Partnership for the Hydrogen Economy (IPHE) signed the IPHE Terms of Reference on November 21, 2003 at a ceremony held in Washington, D.C. The ministers were joined by more than 700 additional stakeholders from government, industry and the non-profit sector.

[2] *Fuel Cell Vehicles: Race to a New Automotive Future*, U.S. Department of Commerce, Office of Technology Policy, January 2003, p. 37.

[3] *Fuel Cells: The Opportunity for Canada*, PricewaterhouseCoopers, June 2002, 68p.

3. Overview of the Transition to a Hydrogen Economy

Hydrogen energy development is one of the Department's top priorities. The President's Hydrogen Fuel Initiative calls for an increasing federal commitment to R&D that will accelerate industry's ability to make a commercialization decision on hydrogen-based transportation technologies. The *National Hydrogen Energy Roadmap*, released by Secretary Abraham on November 12, 2002, and the supporting hydrogen *Vision*, provide a guide for the Department's efforts. The sections below summarize some of the highlights of the *Vision* and *Roadmap* and describe key elements of the transition process.

Technology Readiness of Hydrogen

Although hydrogen is the most abundant element in the universe, it must be produced from other hydrogen-containing compounds such as fossil fuels, biomass, or water. Each method of production requires a source of energy, i.e., thermal (heat), electrolytic (electricity), or photolytic (light) energy. Hydrogen is either consumed on site or distributed to end users via pipelines, trucks, or other means. Hydrogen can be stored as a liquid, gas, or chemical compound and is converted into energy through fuel cells or by combustion in turbines and engines. Fuel cells now in development will not only provide a new way to produce power, but will also improve energy conversion efficiency, especially in transportation applications.

The U.S. chemical and refining industries have a limited number of commercial facilities in place for the production and delivery of hydrogen (about nine million tons is manufactured annually for use in these industries). Those operations are localized, and cannot provide the technology advances and carbon management required for widespread use of hydrogen in the energy sector (i.e., large-scale, low-cost production methods, and storage and delivery infrastructures compatible with automotive and distributed generation applications). Currently, technical challenges remain (centered around cost, performance, and safety) in the elements of the hydrogen energy infrastructure shown in Figure 4. Addressing these challenges will require a coordinated, multi-agency effort. More detailed information on the status of hydrogen technology today and the associated challenges is provided in the National Hydrogen *Vision* and *Roadmap*.

Long-Term Vision of the Hydrogen Economy

In the long-term vision of the hydrogen economy (which will take several decades to achieve), hydrogen will be available in all regions of the country and will serve all sectors of the economy. It will be produced from fossil fuels (with carbon capture and sequestration), renewable energy, and nuclear energy. It will be used throughout the transportation, electric power, and consumer sectors. Hydrogen will be produced in centralized facilities, in distributed facilities at power parks, fueling stations, rural areas, and community locations. Hydrogen production and storage costs will be competitive; the basic components of a national hydrogen delivery and distribution network will be in place; and hydrogen-powered fuel cells, engines, and turbines will have become mature technologies in mass production for use in cars, homes, offices, and factories.

Figure 4. Hydrogen Energy System Elements and Challenges

HYDROGEN VISION ELEMENTS	KEY TECHNICAL CHALLENGES
PRODUCTION Hydrogen will be centrally produced in large refineries, energy complexes, or at renewable or nuclear power facilities, and locally produced in power parks, fueling stations, communities, rural areas, and on-site at customers' premises. Thermal, electric, and photolytic processes will use fossil fuels, biomass, or water as feedstocks and release little or no carbon dioxide into the atmosphere.	♦ Low cost hydrogen production techniques ♦ Low cost and environmentally sound carbon capture and sequestration technologies ♦ Advanced hydrogen production techniques from fossil fuels, renewable, and nuclear resources
DELIVERY A national supply network will evolve to accommodate both centralized and decentralized production facilities. Pipelines will distribute hydrogen to high-demand areas. Trucks and other means will distribute hydrogen or liquid or solid hydrogen carriers to rural and other lower-demand areas.	♦ Lower-cost hydrogen transport technology ♦ Appropriate codes and standards ♦ Right of way for new delivery systems
STORAGE A selection of relatively lightweight, low-cost, and high storage density (low-volume) hydrogen storage devices will be available in a variety of sizes to meet different energy needs.	♦ Low cost, light weight, and energy dense storage systems
CONVERSION Fuel cells will be a mature, cost-competitive technology in mass production. Advanced, hydrogen-powered energy conversion devices such as combustion turbines and reciprocating engines will enjoy widespread commercial use.	♦ Low cost, durable, and reliable fuel cells that can be mass produced
APPLICATIONS Hydrogen will be available for every end-use energy need in the economy, including transportation, central and distributed electric power, portable power, and combined heat and power for buildings and industrial processes.	♦ Successful field tests and demonstrations ♦ Supportive public policies to stimulate infrastructure and market readiness
CODES AND STANDARDS/EDUCATION AND SAFETY Two families of model building codes will be published and available for adoption by local jurisdictions that reference comprehensive equipment standards for hydrogen and fuel cell technologies for commercial and residential applications.	♦ Published fuel gas code that includes hydrogen ♦ Published safety standard for certification of a fuel cell vehicle ♦ Insurance rating of hydrogen energy systems ♦ Training and certification program for code and building officials

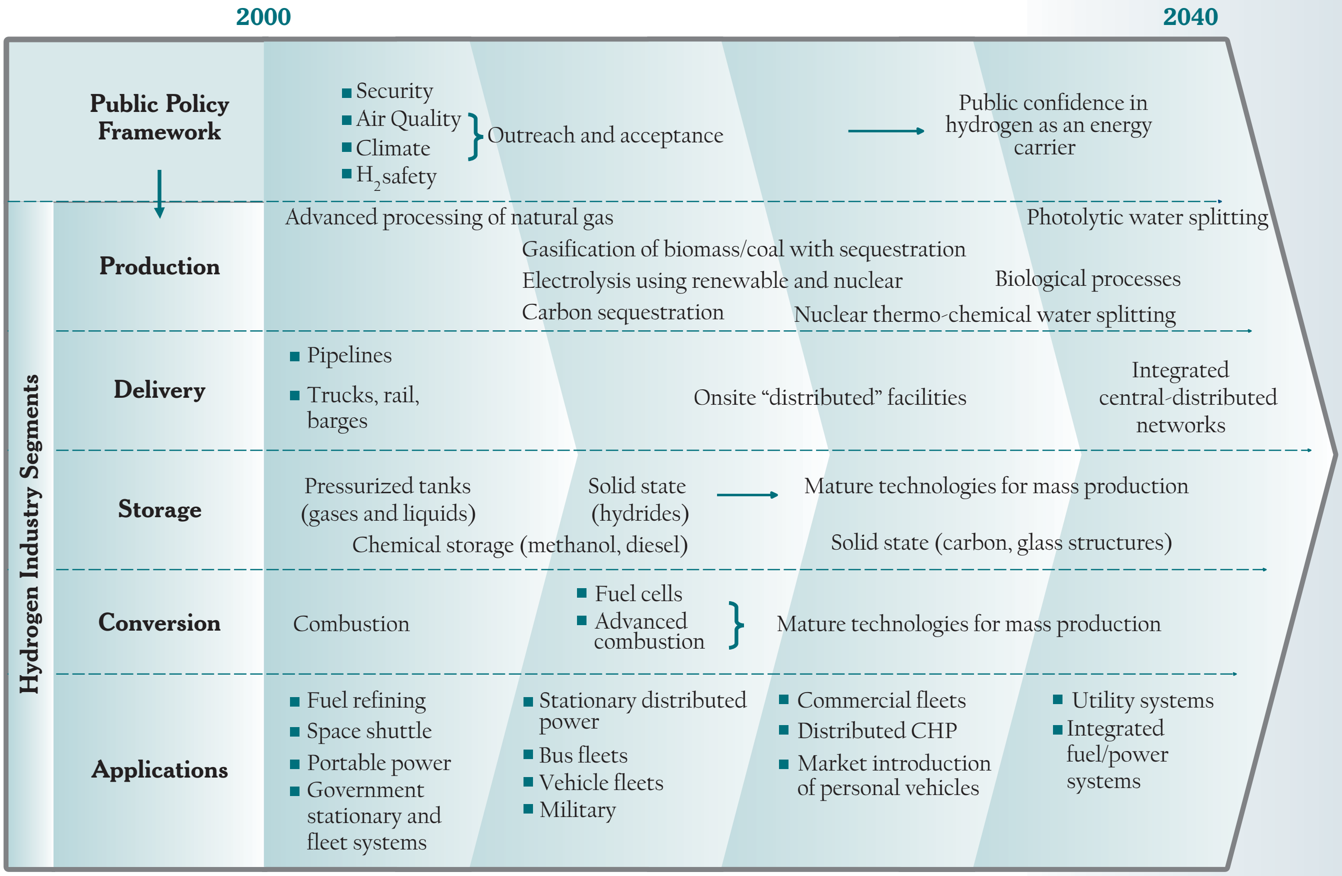
Hydrogen will be the dominant fuel for government and transit bus fleets. It will be used in personal vehicles and light duty trucks. Hydrogen will be combusted directly in turbines and reciprocating engines to generate electricity and thermal energy for homes, offices, and factories. It will be used in fuel cells for both mobile and stationary applications. U.S. companies that commercialize hydrogen technologies will be exporting products and services around the world. Developing countries will have access to clean, sustainable, economical hydrogen-based energy systems to meet their growing energy demands.[4]

Getting from Here to There

Achieving this vision will require a combination of technological breakthroughs, market acceptance, and large investments in a national hydrogen energy infrastructure. Success will not happen overnight, or even over years, but rather over decades; it will require an evolutionary process that phases hydrogen in as the technologies and their markets are ready. Figure 5 presents one way in which this transition might occur.

[4] *A National Vision of America's Transition to a Hydrogen Economy to 2030 and Beyond*, U.S. DOE, February 2002.

FIGURE 5. TRANSITION TO THE HYDROGEN ECONOMY



In the near- to mid-term, most hydrogen will likely be produced by technologies that do not require a new hydrogen delivery infrastructure – i.e., from distributed natural gas and electrolysis of water using electricity (with emphasis on renewable sources such as wind power). As research, development and demonstration (RD&D) efforts progress along renewable, nuclear, and clean coal and natural gas production pathways, a suite of technologies will become available in the mid- and longer-term to produce hydrogen from a diverse array of domestic resources. The economic viability of these different production pathways (samples of which are shown in Appendix A) will be strongly affected by regional factors, such as feedstock availability and cost, delivery approaches, and regulatory environment.

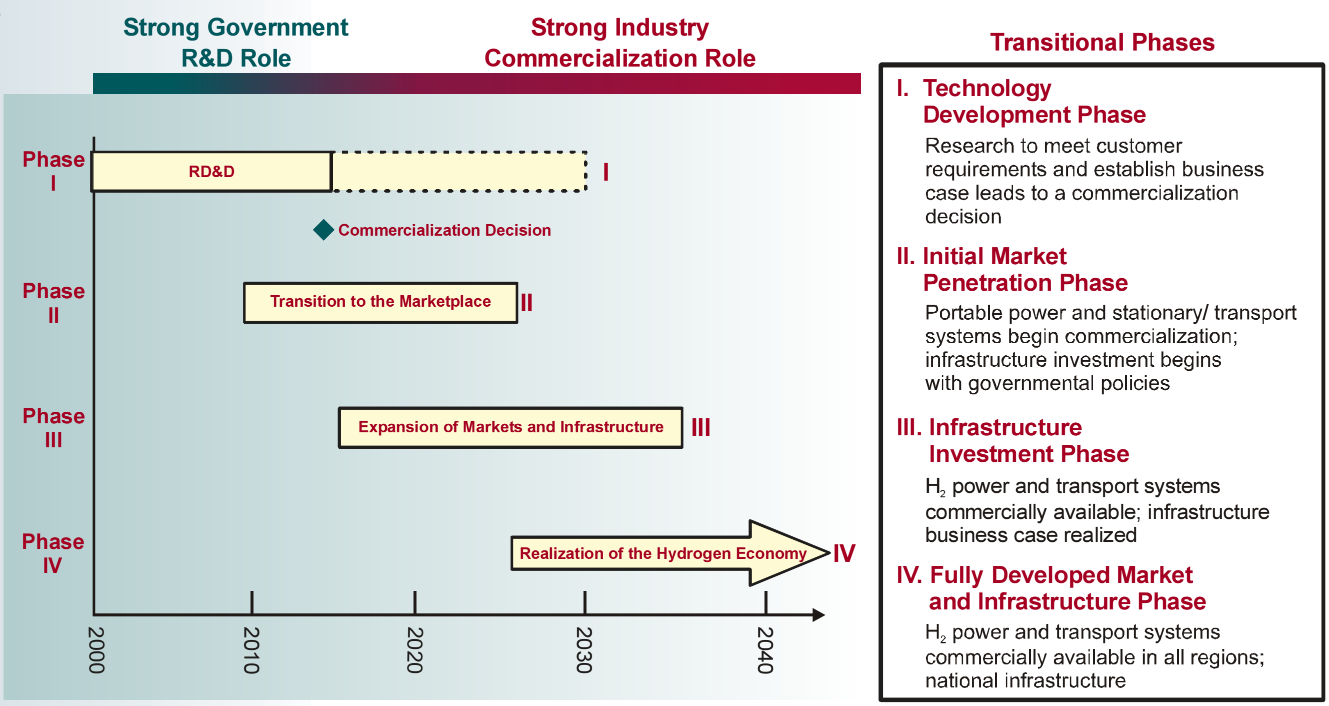
For hydrogen to become a viable fuel source, advanced hydrogen storage technologies will also be required, especially for automotive applications. Current storage systems are too heavy, too large, and too costly. Technologies to convert hydrogen into useful energy—fuel cells and combustion technologies—must be further improved to lower cost and improve performance. Finally, the infrastructure to deliver hydrogen where it is needed must be developed and constructed. The hydrogen infrastructure can evolve along with the conversion and production technologies, since most of the infrastructure that is developed for fossil-based hydrogen will also be applicable to renewable- and nuclear-based hydrogen. Infrastructure will begin with pilot projects and expand to local, regional, and ultimately national and international applications. More detailed economic analyses of the different production, storage, conversion and distribution options will also be essential.

As shown in Figure 6, a full transition to a hydrogen-based energy system will take several decades and require strong public and private partnership. In Phase 1, government and private organizations will research, develop, and demonstrate "critical path" technologies and safety assurance prior to investing heavily in infrastructure. Public education and codes and standards must be developed concurrently with the RD&D. The President's Hydrogen Fuel Initiative is consistent with completion of the critical path technology RD&D phase leading up to a commercialization decision in 2015. This Phase could continue beyond 2015 to support basic science and to further develop advanced, sustainable technologies for hydrogen production and use. The commercialization decision criteria will be based on the ability of hydrogen fuel technology to meet customer requirements and to establish the business case.

Phase II, Transition to the Marketplace, begins as industries begin to manufacture and market hydrogen (using the existing natural gas and electric grid infrastructure) and fuel cell technologies in portable, stationary, and transportation applications. Consumers will need compelling reasons to purchase these products; public benefits such as high efficiency and low emissions are not enough. The all-electronic car powered by hydrogen fuel cells (such as the General Motors Hy-wire) is one example of value delivery; it offers the consumer much improved performance through elimination of mechanical parts and greater design flexibility through the "skateboard" approach with "snap-on" bodies. During this phase, government agencies will work to develop codes and standards required for the transition. Government and industry involvement continue as hydrogen-related technologies meet or exceed customer requirements.

As these markets become established, government can foster their further growth by playing the role of "early adopter" and by creating policies that stimulate the market. Phase III, Expansion of Markets and Infrastructure, proceeds if industry makes a positive commercialization decision in 2015. During this phase the business case for a hydrogen-

Figure 6. Government-Industry Roles in the Transition to a Hydrogen Economy



based economy is realized, attracting investment in infrastructure for fuel cell manufacturing and hydrogen production and delivery. Government policies still may be required to nurture this infrastructure expansion phase. Phase IV, several decades from now, is Realization of the Hydrogen Vision, when consumer requirements will be met or exceeded, national benefits in terms of energy security and improved environmental quality are achieved, and industry can receive adequate return on investment and compete globally.

4. DOE Hydrogen Program

Program Mission

The central mission of the DOE's Hydrogen Program is to research, develop, and validate fuel cell and hydrogen production, delivery, and storage technologies. Hydrogen from diverse domestic resources will then be used in a clean, safe, reliable, and affordable manner in fuel cell vehicles and stationary power applications. Development of hydrogen energy will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the Nation's prosperity throughout the 21st century.

Program Strategy

DOE is currently conducting research, development, demonstrations, standards formulation, and public outreach and education activities. These activities are carried out in partnership with automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, other federal agencies, state government agencies, universities, national laboratories, and other stakeholder organizations.

These activities address the development of hydrogen energy systems for transportation, stationary power, and portable power applications. Stationary power applications include combined heat and power generation systems in buildings and manufacturing facilities, utility-scale power systems, and distributed (smaller-scale) power systems. Transportation applications include fuel cell and hydrogen infrastructure development. DOE-funded activities include cost-shared, public-private partnerships to address the high-risk, critical technology barriers preventing widespread use of hydrogen as an energy carrier. These efforts are augmented by fundamental and applied research at national laboratories and universities.

DOE is funding RD&D efforts that will provide the basis for the near-, mid-, and long-term production, delivery, storage, and use of hydrogen derived from fossil fuel, nuclear, and renewable sources. Reforming of distributed natural gas and electrolysis will be the most efficient and economical way to produce hydrogen for near-term applications, but costs are still too high.

As reflected in the Administration's FutureGen project (also known as the Integrated Sequestration and Hydrogen Research Initiative), technologies will continue to be evaluated and developed to produce low-cost hydrogen from domestic and secure sources of coal with the capture and sequestration of CO_2. With the implementation of carbon management strategies, coal will play a key role in the long term because of its abundance and low cost. Hydrogen from renewable biomass feedstocks can benefit from gasification, reforming, and separation technologies developed for fossil resources. The production of hydrogen from non-conventional sources such as biological materials will be explored through fundamental basic science.

To address the need for sustainable energy supplies, DOE is also investigating advanced methods of hydrogen production from renewable and nuclear resources, and more advanced systems for storing and delivering hydrogen in an expanded hydrogen market.

The DOE will focus on methods to produce affordable supplies of hydrogen from water using renewable electricity (e.g., solar, wind) and nuclear sources of energy, or even using direct solar conversion or biological methods. A mix of diverse energy feedstocks to produce hydrogen is needed to gradually make the transition to a sustainable, secure, affordable, and environmentally safe hydrogen energy system.

FY05 Program Activities and Highlights

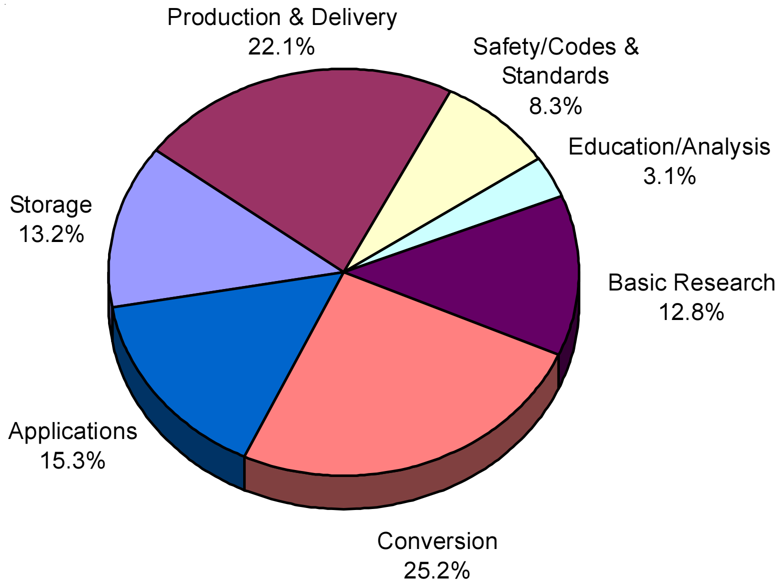
The DOE Hydrogen Program funds efforts in the following areas, which support the National Hydrogen Energy *Vision* and *Roadmap*.

- Production and Delivery
- Storage
- Conversion
- Basic Research
- End-use Applications
- Education/Systems Analysis
- Safety/Codes and Standards

These areas are necessarily interrelated, with developments in one segment relying on corresponding developments in other segments. An integrated approach to RD&D within the Department will ensure that, regardless of the pathway, common challenges are efficiently addressed. Figure 7 shows how the DOE budget request for FY05 breaks out into the program areas.

Associated RD&D includes efforts that are necessary to achieve a hydrogen energy pathway (e.g., high-temperature stationary fuel cells, carbon sequestration and carbon management, hybrid electric vehicle research as part of the FreedomCAR partnership,

Figure 7. DOE Hydrogen Technology Budget Request - FY05 (%)



TOTAL: $227 Million

and coal and biomass gasification), but which are likely to be funded even if there were no DOE hydrogen program. The President's Hydrogen Fuel Initiative reflects an enhanced hydrogen and fuel cell program to accelerate technology development and demonstration activities. This enhanced program will facilitate commercialization decisions by industry in the year 2015, allowing rapid market penetration and significant oil displacement and environmental benefits for the year 2030 and beyond. The budget includes an increasing emphasis on exploratory research for hydrogen production, storage, and end use applications. RD&D on hydrogen conversion continues at essentially steady levels, with some shifts to increase or decrease emphasis on particular technologies or pathways. Ongoing work in two important DOE-industry partnerships continues: FreedomCAR and the Solid State Energy Conversion Alliance (SECA).

The following sections provide an overview of key DOE FY05 hydrogen activities in production, delivery, storage, conversion, basic research, applications and education, and safety/codes and standards.

Production and Delivery

- Conduct research on lowering costs of distributed hydrogen production from natural gas, including:
  - Membranes
  - Catalytic hot oxygen reactor
- Conduct coal-derived hydrogen program.
  - Continue computational science and research studies on advanced systems for producing hydrogen from liquid carriers
  - Research to develop advanced separation, cleanup and process intensification technology to produce lower-cost hydrogen
  - RD&D to integrate carbon capture and sequestration technologies into fossil-based production systems
- Accelerate and expand research on the production of hydrogen from renewable resources including
  - Electrolysis cost reduction
  - Thermochemical conversion of biomass
  - Photolytic and fermentative micro-organism systems
  - Photoelectrochemical systems and water electrolysis
  - High-temperature chemical cycle water splitting and other non-carbon emitting high temperature technology
- Conduct research to develop a multi-fuel, oxygen-blown, integrated gasification combined cycle system that can produce hydrogen and power.

Fossil Energy Focuses on Hydrogen From Coal

The Office of Fossil Energy (FE) will build upon ongoing RD&D activities within FE to demonstrate low-cost, novel, and advanced hydrogen production and delivery technologies from coal by 2015. These technologies include advanced shift and separation technologies including membranes for producing hydrogen from coal, cost- effective removal of carbon dioxide and trace components, and optimal synthesized gas-derived liquid fuels for fuel cell applications. Integration of these technology modules into advanced coal power plants will allow production of affordable hydrogen from domestic fossil energy with essentially zero air emissions.

FutureGen: Emission-Free, Coal-Fired Electricity and Hydrogen Production

On February 27, 2003, President Bush announced that the United States would sponsor a $1 billion, 10-year initiative to create the world's first coal-based, zero emissions power plant to produce electricity and hydrogen. In support of this announcement, Secretary of Energy Abraham unveiled plans for a new DOE initiative called FutureGen. This project will establish the technical and economic feasibility of producing electricity and hydrogen from coal while capturing and sequestering the carbon dioxide generated in the process. FutureGen will be designed and constructed with the flexibility to conduct both full scale and slipstream tests of advanced technologies. These advanced technologies offer the promises of clean environmental performance at a reduced cost and increased reliability. FutureGen will showcase cutting-edge technologies that can virtually eliminate environmental concerns associated with coal utilization.

Nuclear Hydrogen Activities Will Harness Heat to Produce Hydrogen From Water

The Office of Nuclear Energy, Science & Technology will work with its partners to demonstrate the commercial-scale production of hydrogen using heat from a nuclear energy system by 2017. In addition to the emission-free electricity currently produced by nuclear reactors, some advanced nuclear reactor designs operate at very high temperatures, making them well-suited to drive highly efficient hydrogen production processes. Several reactors selected for further research and development under the Generation IV Nuclear Energy Systems Initiative (GenIV) are capable of high-efficiency hydrogen production.

The Solid State Energy Conversion Alliance (SECA) Will Fast-Track Commercialization of Solid Oxide Fuel Cells

SECA is a joint government-industry effort to achieve cost and technology breakthroughs in solid oxide fuel cell (SOFC) development within a short period of time. The goal is to create a solid oxide fuel cell (3-10 kW) that can be mass produced in modular form. Used individually or in clusters, depending upon the amount of energy required, these fuel cells will be able to power a broad array of applications. Identified technical challenges include: fuel processing and manufacturing; controls and diagnostics; power electronics; modeling and simulations; and materials. A five- to ten-fold cost reduction over existing technology is required to reach the goal of producing SOFCs at a cost of $400/kW. Key milestones include:

2010: Demonstrate 3-10kW fuel cells at $400/kW with target efficiencies of 40-60%.

2015: Demonstrate hybrid fuel cell/turbines that meet $400/kW system requirements with 70-80% efficiencies.

- Initiate Nuclear Hydrogen Initiative.
  - Issue Nuclear Hydrogen R&D Plan
  - Begin R&D on baseline hydrogen production processes (high-temperature electrolysis and sulfur-based thermochemical cycles)
- Conduct research to develop technology for gas/liquids produced from biomass to supply cost-effective renewable-based hydrogen.
- Conduct research to lower the cost and improve the energy efficiency of hydrogen compression and liquefaction.
- Conduct research to lower the cost of hydrogen delivery infrastructure, including development of improved, lower cost materials for hydrogen pipelines and new liquid or solid hydrogen carriers.

Storage

- Complete research, including materials work, to validate high-pressure and cryogenic tanks for near-term approaches.
- Emphasize research and evaluation of innovative storage approaches including reversible storage materials, such as carbon nanotubes and metal hydrides; regeneration issues related to chemical hydrides; and options for hybrid approaches that combine compressed gas storage with reversible materials.

Conversion

- Continue RD&D to lower cost and improve durability of polymer electrolyte membrane fuel cell for transportation and small stationary applications.
- Initiate development of auxiliary power unit systems for heavy vehicle application.
- Downselect for further development and demonstrate baseline performance of high temperature membranes.

Basic Research

- Conduct research in novel materials for hydrogen storage with major research components in complex hydrides; nanostructured materials; theory, modeling, and simulation approaches; and novel analytical and characterization tools.

- Investigate membrane materials for separation, purification, and ion transport to include major research programs in integrated nanoscale architectures; fuel cell membranes; and theory, modeling, and simulation of separation processes and mechanisms.

- Design of catalysts at the nanoscale with the main emphasis on nanoscale phenomena; innovative synthetic techniques; novel characterization techniques; and theory, modeling, and simulation of catalytic pathways.

- Investigate bio-inspired materials and processes to include studies of enzyme catalysts; bio-hybrid energy coupled systems; and theory, modeling and nanostructure design.

- Conduct research to explore solar energy-based hydrogen production with the emphasis on nanoscale structures; light harvesting and novel photoconversion concepts; organic semiconductors and other high performance materials; and theory, modeling, and simulation of photochemical processes.

Basic Research Will Target Breakthroughs in Key Areas

Recent advances in nanosciences, catalysis, modeling, simulation, and bio-inspired approaches offer exciting new research opportunities for addressing both short-term showstoppers and long-term grand challenges to the practical realization of a hydrogen economy. DOE's Office of Science seeks to foster revolutionary advances in hydrogen production, delivery, storage, and conversion technologies in the following five critical basic research areas: Novel Materials for Hydrogen Storage; Membranes for Separation, Purification, and Ion Transport; Design of Catalysts at the Nanoscale; Bio-Inspired Materials and Processes; and Solar Hydrogen. The basic hydrogen research program will be coordinated with the needs of applied research and development, and will employ coupled experimental and theoretical components for maximum impact. The integration will ensure that discoveries and related conceptual breakthroughs achieved in basic research programs will provide a foundation for the innovative design of materials and processes that will produce improvements in the performance, cost, and reliability of hydrogen production, storage, and use. For more information on how basic research can help overcome technical challenges to a hydrogen economy, see the recent Basic Energy Sciences report at http://www.sc.doe.gov/bes/hydrogen.pdf.

Applications

- In collaboration with DOT and EPA, conduct hydrogen infrastructure and fuel cells vehicle demonstration project to validate technology status and refocus RD&D.
  - Hydrogen fueling station safety, operations, reliability, and vehicle interface/fuel dispenser systems
  - Vehicle performance and reliability under real operating and climate conditions

- Validate safety and performance data from power park systems to co-produce hydrogen and electricity for vehicles and grid, respectively.

Education and Safety/Codes and Standards

- Implement training program for elementary and secondary school teachers.

- In coordination with DOT, conduct educational campaign to communicate hydrogen benefits, safety, and utilization information to key stakeholders.

- In coordination with the DOT, conduct top-down safety analysis of all hydrogen-related processes and equipment for transportation and stationary applications and begin identifying design requirements.

- In coordination with the DOT, assist national and international code developers in developing new building codes and equipment standards.

- Implement comprehensive safety testing and evaluation program for hydrogen fuel cell vehicles, in collaboration with DOT, EPA, NIST and other agencies.

- Develop comprehensive economic model to analyze technology options and tradeoffs.

FreedomCAR Aims to Overcome Hydrogen-Powered Fuel Cell Research Hurdles

FreedomCAR is a government-industry partnership between the U.S. Department of Energy and the U.S. Council for Automobile Research (members include Ford Motor Company, General Motors Corporation, and DaimlerChrysler Corporation). The collaboration was formed to jointly research high-efficiency, clean cars as part of an effort to reduce American dependence on foreign oil. The C-A-R in FreedomCAR stands for Cooperative Automotive Research.

The long-term strategic goal of FreedomCAR participants is to develop technologies for hydrogen-powered fuel cell vehicles that are not dependent on oil and emit no harmful pollutants or greenhouse gases. The aim is to achieve this technology shift without sacrificing mobility or freedom of choice for American consumers. In the near term, FreedomCAR will support a wide range of hybrid electric vehicle technologies that are designed to reduce oil consumption and vehicle tailpipe emissions.

Participants will work together to develop technologies that will eventually enable the mass production of affordable hydrogen-powered fuel cell vehicles and the hydrogen infrastructure to support them. The Partnership Plan identifies technology milestones to measure progress in 2010 and 2015 (these can be downloaded from www.eere.energy.gov/vehicle.html). Some of the key 2010 milestones include:

- Electric propulsion system with a 15-year life and capability to deliver at least 55 kW for 18 seconds, and 30 kW continuously at a system cost of $125/kW peak.
- Internal combustion engine powertrain systems that cost $30/kW, have a peak brake engine efficiency of 45%, and meet or exceed emission standards.
- Electric drivetrain energy storage with a 15-year life at 300Wh and with a discharge power of 25 kW for 18 seconds at a cost of $20/kW.
- Material and manufacturing technologies for high-volume production vehicles that enable/support the simultaneous attainment of affordability, increased use of recyclable/renewable materials, and a 50% reduction in the weight of the vehicle structure and subsystems.

DaimlerChrysler NECAR5

Ford P2000 Prodigy

GM HydroGen1

Program Milestones

The milestone chart shown in Figure 8 presents the key activities of DOE's Hydrogen Program through completion of the critical path technology development phase in 2015. Technology development is projected to continue beyond 2015 to support basic science and RD&D on advanced technologies and renewable hydrogen production alternatives. The milestones are organized according to the National Hydrogen Energy Vision and Roadmap's six key elements.

Milestones for each of the timelines specify a delivery date for the given technology development, improvement, or demonstration. The values given are compiled from the best available primary sources, including DOE analysis, the FreedomCAR Partnership Plan, the National Hydrogen Energy Roadmap, and ongoing Federal laboratory research. As technologies evolve and economic and systems analyses progress, these targets will be refined.

The milestones listed in Figure 8 describe DOE hydrogen RD&D activities at a high level of aggregation and may not articulate all component activities represented by the milestone. The timelines do not list all of the interim milestones for each pathway, nor do they include every critical go/no-go decision point and technology option downselect point integral to each activity at the sub-program and project level. Some production technologies, such as photoelectrochemical, may require longer development beyond 2015 to be cost-competitive with other hydrogen production methods.

For each milestone in Figure 8, the most appropriate measurement units are provided in the legend. For some technologies, costs are primarily associated with scale (e.g., dollars per megawatt of capacity); for others, costs are associated with delivered hydrogen (e.g., dollars per gallon of gasoline equivalent, or gge). The term "project to" means that the technology demonstrated at the indicated time point would meet the specified cost target if that technology were in full commercial-scale production.

Budget Outlook

The President's Hydrogen Fuel Initiative will put the program on track to meet the 2015 milestones listed here.

As technical milestones are achieved, DOE will need to invest resources to overcome barriers to commercialization and infrastructure development. An increased focus on educating consumers about the safe use of hydrogen and its benefits will be essential to enhance awareness and acceptance of the technology. Detailed analysis of life-cycle costs and benefits and environmental impacts will continue to support decisions regarding future hydrogen related research.

Out-year planning will identify needs to expand RD&D on production and storage technologies, delivery infrastructure, and education and safety/codes and standards. The $1.2 billion Hydrogen Fuel Initiative proposed by President Bush for 2004-2008 includes $720 million in new R&D funding. Some specific activities that would be pursued with this funding in the next five fiscal years include:

Production – Lowering production costs is a top priority. A National Academies' study, requested by DOE and just completed, provides insight for a hydrogen feedstock

Figure 8. Technology Development Timeline (Phase I): Milestones and Decision Points

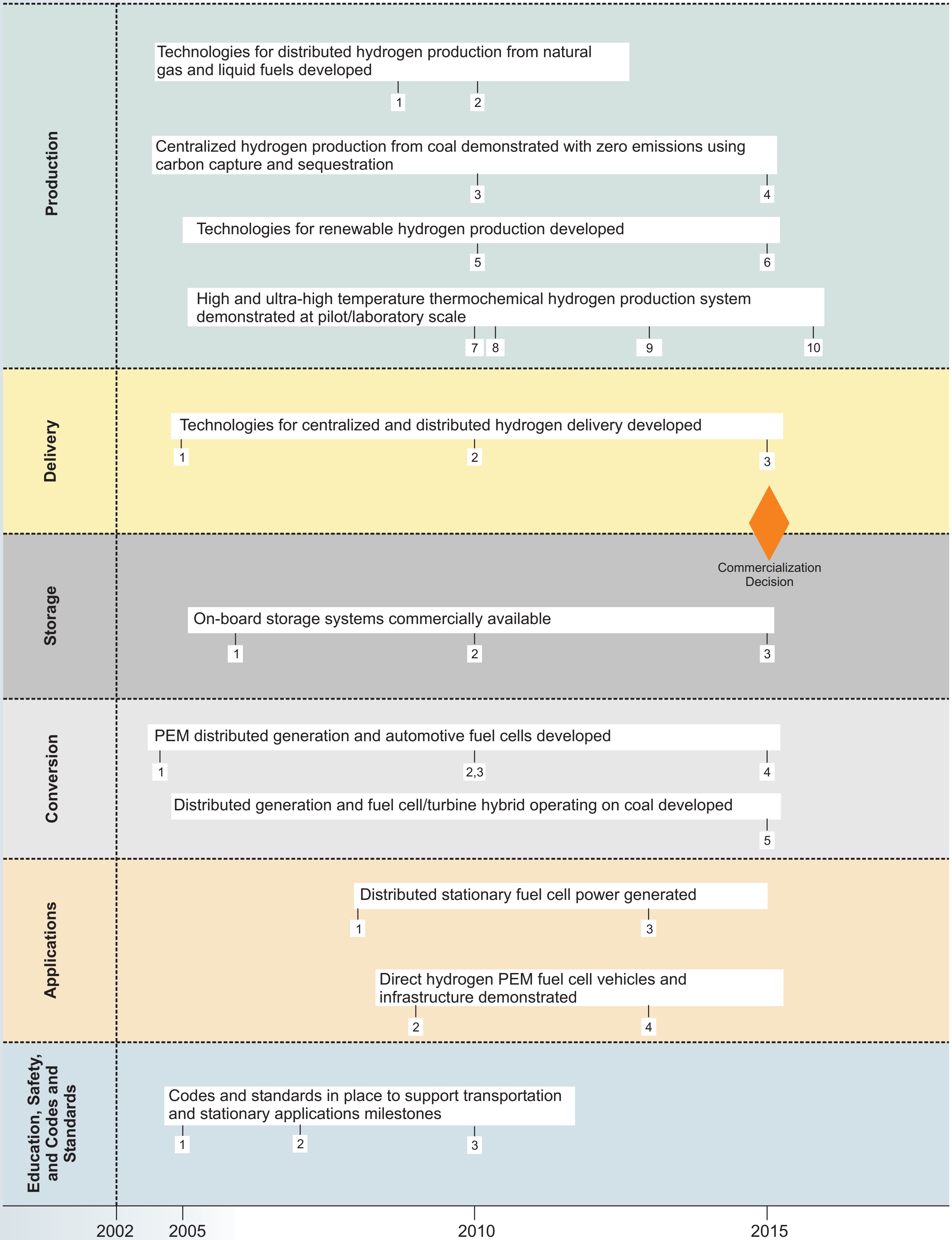


Figure 8 (cont'd). Legend for Technology Development Timeline (Phase I)

Production Milestones

Distributed Natural Gas/ Liquid Fuels*

1. 2009: Develop technology to produce distributed hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $2.50/gge for hydrogen. [At the pump, untaxed, no carbon sequestration]
2. 2010: Develop technology to produce hydrogen from natural gas or liquid fuels at a refueling station that projects to a cost of $1.50/gge for hydrogen. [At the pump, untaxed, no carbon sequestration, at 5000 psig]

Central Coal*

3. 2010: Develop pilot scale membrane separation and reactive/membrane separation technology for hydrogen production that meets cost targets.
4. 2015: Demonstrate a zero emission coal plant producing hydrogen and power with carbon capture and sequestration at a 25% cost reduction that projects to $0.80/gge at the plant gate ($1.80/gge delivered).

Renewable Resources

5. 2010: Develop technologies for integrated wind hydrogen production at $2.85/gge delivered assuming a 500 gge/day electrolyzer system and $0.04/kWh wind electricity (2015: $2.25/gge).
6. 2015: Demonstrate laboratory-scale biological system to produce hydrogen at a cost that projects to $10/gge at the plant gate ($11/gge delivered). Demonstrate laboratory-scale photoelectrochemical water splitting at a cost that projects to $5/gge at the plant gate ($6/gge delivered). The long term goal for these hydrogen production technologies is to be competitive with gasoline.

High-Temperature Thermochemical

7. 2010: Laboratory-scale demonstration of ultra-high-temperature thermochemical hydrogen production from solar reactors that project to a cost of $2.50/gge ($3.80/gge delivered).
8. 2011: Pilot-scale demonstration of high-temperature thermo-chemical production for use with nuclear reactors that projects to a cost of $2.50/gge ($3.50/gge delivered).
9. 2013: Design of engineering scale nuclear hydrogen production system completed.
10. 2017: Engineering-scale demonstration of thermochemical hydrogen production system with cost that projects to less than $2.00/gge at the plant gate ($3/gge delivered) using heat from nuclear reactors.

Storage Milestones

1. 2006: Downselect hydrogen storage options with potential to meet 2010 targets.
2. 2010: Develop and verify on-board storage systems achieving: 6% by weight capacity and 1500 watt hours/ liter energy density at a cost of $4.00/kWh of stored energy.
3. 2015: Develop and verify on-board storage systems achieving: 9% by weight capacity, 2700 watt hours/ liter, and $2.00/kWh.

Applications Milestones

1. 2008: Validate first regional networks with fuel cell systems that project a cost of less than $1,250/kW.
2. 2009: Direct hydrogen polymer electrolyte membrane fuel cell vehicles demonstrated at multiple sites, achieving 2,000 hours durability.
3. 2013: Validate stationary fuel cell system that co-produces hydrogen and electricity at 40,000 hours durability with 40% efficiency at a cost of $750/kW or less.
4. 2013: Validate direct hydrogen polymer electrolyte membrane fuel cell vehicles achieving 5,000 hours durability (service life of vehicle) and 300 mile range.

Phase 1 Commercialization Decision: 2015

Based on technology development success in meeting customer requirements and establishing a business case.

Conversion Milestones

1. 2004: On-board fuel processing Go/No Go decision based on ability to achieve 78% efficiency and <0.5 minute start time.
2. 2010: Distributed stationary generation natural gas/ propane 50-250 kW fuel cell developed: 40% electrical efficiency, 40,000 hours durability (equivalent to service life between major overhauls), at a cost of less than $400-$750/kW.
3. 2010: Develop direct hydrogen polymer electrolyte membrane automotive fuel cell operating at 60% peak efficiency, 220 W/L density, 325 W/gge specific power at a cost of $45/kW (automotive production quantity).
4. 2015: Polymer electrolyte membrane automotive fuel cell meets cost of $30/kW.
5. 2015: Fuel cell/turbine hybrid operating on coal developed at a cost of $400/kW with a system efficiency of 70% with carbon sequestration.

Education, Safety, and Codes and Standards Milestones

1. 2005: Publish codes and standards models and safety and training materials.
2. 2007: Education program on safety in place.
3. 2010: Technical codes and standards in place to support regulatory standards.

Delivery Milestones

1. 2005: Define a cost-effective hydrogen fuel delivery infrastructure for supporting the introduction and long-term use of hydrogen for transportation and stationary power.
2. 2010: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.30/gge of hydrogen.
3. 2015: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen.

* *The assumed feedstock cost for natural gas is $4.00/million Btu and the assumed cost for coal is $29.00/short ton.*

strategy for the transition and long term. The study will help DOE set priorities for research needs in out-year planning.

The development of small-scale natural gas reformer and electrolysis technologies are needed as part of the transition to the market place. Development efforts are required for natural gas-to-hydrogen generation technologies that can be mass-produced and operated reliably and safely in a typical fueling station with remote operations control to reduce costs. Technologies using partial oxidation (or autothermal reforming) and steam methane reforming processes should be further developed for high energy efficiencies. In electrolysis technology, reduced capital costs, enhanced system efficiency, and improved durability for distributed-scale hydrogen production from renewable-sourced electricity and water is needed. Lower-cost membranes and catalysts that can operate at higher temperatures and pressures need development as well as improved system integration to lower the cost of manufacturing. Emphasis is needed in component development and systems integration to enable electrolyzers to operate from inherently intermittent and variable-quality power derived from wind and solar sources. The aim is to partner with industry to create robust, efficient and cost-effective wind-electrolysis-hydrogen systems that will be ready for deployment as the distributed hydrogen infrastructure begins to develop.

The development of technologies and feedstocks for high-volume, efficient, centralized production of hydrogen is needed. For example, development efforts are required to simplify reforming processes using advanced catalysts and reactors; to develop durable membranes for separating hydrogen from coal-based syngas; and to develop high-temperature, thermochemical processes (e.g., sulfur-iodine) using solar and nuclear-generated heat. This latter activity could lead to the construction of an advanced demonstration nuclear plant with electricity and hydrogen co-production capabilities.

Basic research is needed to produce breakthroughs in catalysis and separations and to improve the understanding of carbon sequestration. Recent advances in nanoscale and molecular synthesis, such as characterization tools that allow active sites to be probed directly; modeling of complex chemical systems; and high-throughput synthesis and screening methods will support future catalyst research. A better understanding of light-induced dynamic processes in molecules, polymers, and semiconductor nanoparticles will support the development of low-cost solar cells and photocatalysts. Research on new semiconductors, polymers, supramolecular assemblies, and catalysts will enable the synthesis of two- and three-dimensional chemical systems for efficient light harvesting, charge separation, and fuel formation. These systems may also integrate biological or bio-inspired catalysts. Understanding the pathways by which hydrogen is made and processed in living organisms may enable breakthroughs by providing non-precious metal catalysts that allow fuel processing reactions to run at lower temperatures.

Additional areas of hydrogen production include novel and advanced systems such as advanced shift and separation devices including membranes for producing hydrogen from natural gas, coal, and biomass; cost-effective removal of carbon dioxide and trace components; and optimal synthesis gas-derived liquid fuels for decentralized reforming of hydrogen for fuel cell applications. Enhanced research on production of hydrogen from renewable resources (including conversion of biomass, photolytic and fermentative micro-organism systems, photoelectrochemical systems, and water electrolysis) will help to achieve the long term goal for cost-competitive hydrogen production from non carbon emitting domestic resources such as solar and wind energy.

Delivery – Delivery technologies and economics will heavily influence the level of infrastructure investment needed. Systems analysis of delivery alternatives will show the life-cycle cost advantages and disadvantages of transporting hydrogen over long distances and will identify areas in which cost reductions would provide the greatest value. New concepts will be needed to reduce delivery costs from the point of production to refueling stations and distributed power facilities. This effort could involve the development of lower-cost liquefaction technologies or the use of metal or chemical hydrides, carbon nanotubes, or other advanced hydrogen reversible liquid or solid carrier concepts that can increase the energy density of hydrogen transport. Existing natural gas pipelines could be used to carry a mixture of 20 percent hydrogen in natural gas. The main difference in a hydrogen pipeline grid compared to the existing natural gas pipeline is in the materials of construction. Efforts to ensure the safety of the hydrogen delivery system need to be coordinated with the Department of Transportation. In addition, low-cost compressor technology, pipeline materials, seals, components, and sensors and controls will be needed to lower the capital cost of hydrogen pipelines.

Storage – Lower cost, lighter weight, and higher density hydrogen storage is one of the key technologies needed for the hydrogen economy. A breakthrough in hydrogen storage could have tremendous impact. Advanced storage materials that show promise include alanates, carbon structures, chemical hydrides, and metal hydrides. As leading candidates for low- pressure, solid-state materials emerge, more intense efforts will need to be applied to this "critical path" technology area. Effort will be required to understand how to produce and contain these advanced materials, fill and discharge hydrogen, manage pressure and thermal properties, and integrate them into practical systems for stationary and mobile applications. The emphasis in basic research will be on understanding the chemical and physical processes governing the hydrogen-materials interactions to enable the design and discovery of new, higher efficiency, recyclable hydrogen storage materials. Research will take advantage of the revolutionary new properties and capabilities offered by nanoscience to further enhance storage capacity and to improve uptake/release kinetics. Improvements in today's metal and complex hydrides can be achieved by careful design of two- and three-dimensional nanoarchitectures to improve the weight percentages of stored hydrogen and provide control of hydrogen storage/release. Advances in basic science can also contribute to development of safe "smart" storage tanks that predict and communicate performance attributes and warn of potential failure.

Conversion – Cost reduction (by a factor of approximately 10) and improved durability and reliability will be required to assure the commercial viability of fuel cells in both stationary and mobile applications. Direct hydrogen conversion research will continue on high-efficiency polymer electrolyte membranes (PEM) and other fuel cell stack components and systems to meet cost, durability, power density, heat utilization, start-up time, cycling, load-following and other key performance targets. The high priority fundamental research topics include catalysts, electrochemistry, membranes, and the nanoscale behavior governing the performance and cost of fuel cells. The development of efficient and cost-effective fuel cell technology solutions for automotive and stationary applications presents a grand challenge that will take a substantial and sustained effort in chemical and materials research, combining both near- and long-term strategies. The major needs are all based on improved or new materials. Future efforts in on-board processing of hydrocarbon and alternative fuels to hydrogen will be guided by a major technology review in mid-2004 to assess the technical progress of research conducted to date on fuel processing systems.

Applications – Efforts are needed to demonstrate hydrogen energy systems (including fuel cells, engines, and turbines) in vehicles and distributed energy facilities. Demonstrations provide technical data for informing research programs as well as financial data for determining market and investment risks. Demonstrations are planned for a statistically significant number of hydrogen vehicles, including several locations and refueling stations. These demonstrations will be used to validate predictions of performance, cost, reliability, maintenance, and environmental impacts and to develop a better understanding of the vehicle and infrastructure. In stationary power facilities, demonstrations are needed on a statistically significant number of distributed heat and power systems. Early demonstrations could be conducted at federal facilities such as military bases, hospital complexes, and office buildings.

Codes and Standards – Commercialization of hydrogen technologies cannot proceed unless effective domestic and international codes and standards are in place. DOE, in collaboration with DOT, EPA, NIST, DOD, NASA, and other agencies, can play a role in fostering their development. Future efforts will include the development and dissemination of model building, fire, and safety codes; codes and standards for the hydrogen delivery infrastructure; utility interconnection and safety standards for hydrogen-fueled distributed energy devices; and product safety and performance standards and design requirements for vehicles, fuel cells, storage tanks, and other products and equipment that use hydrogen.

Education and Outreach – Consumer awareness and acceptance of hydrogen products and services will be an essential feature of the hydrogen economy. Federal and state officials, equipment manufacturers, users, and installation and maintenance personnel need to understand how to operate hydrogen technologies in a safe manner. Education and training materials for a variety of audiences need to be developed and disseminated. Target audiences include educators at the elementary, secondary, and university levels; code and zoning officials; professional and trade organizations; real estate developer and building owners and operators; public and private fleet operators; and the general public. These funds would be used to create a curriculum and training program for teachers and to develop educational materials for key target audiences.

Integrated Program Management and Coordination

The DOE Hydrogen Program currently includes participation from the Offices of Energy Efficiency and Renewable Energy (EE), Fossil Energy (FE), Nuclear Energy, Science and Technology (NE), and Science (SC). Each office manages activities that address hydrogen technologies that meet the needs of their respective feedstocks and target applications. As the nation focuses more attention and resources on exploring the potential for a hydrogen energy future, close coordination among these offices becomes critical.

One benefit of a hydrogen economy is its ability to use a diverse set of energy resources for supply. DOE's research activities will provide the United States with a variety of options for producing cost-competitive hydrogen. However, technical challenges associated with hydrogen storage, delivery, conversion, and end-use applications are the same regardless of whether the hydrogen is derived from a renewable, fossil, or nuclear pathway. Fuel cells are being designed to meet the unique needs of particular end-use applications (e.g., stationary generating stations and transportation systems), but these will ultimately be fueled with hydrogen from the energy feedstock mix that makes the most sense, both economically and environmentally, for a particular region.

A Program Management and Operations Plan will be developed to provide more detail on how DOE hydrogen activities will be managed and integrated within the Department. The Office of Energy Efficiency and Renewable Energy, as the lead organization for the President's Hydrogen Fuel Initiative, will designate the DOE Hydrogen Program Manager. Permanent working groups, such as the recently created Interagency Task Force and the DOE Hydrogen Working Group, will meet periodically to share information and coordinate activities. Recommended functions of the DOE Hydrogen Working Group (comprised of representatives of EE, FE, NE, and SC, as well as the Offices of Management, Budget and Evaluation and Policy and International Affairs) include:

- Evaluate the progress of the Department's hydrogen and related activities with regard to milestones and performance goals.
- Strengthen information exchange on technical developments.
- Help ensure that the various activities (e.g., budgeting, execution, evaluation, and reporting) remain well-coordinated.
- Provide suggestions for management improvements and stronger technical performance.
- Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways.

Program oversight and systems integration will be provided by the participating Assistant Secretaries or their equivalents reporting to the Under Secretary for Energy, Science and Environment. This group will monitor overall program costs, schedules, progress toward performance targets, and overlaps. The Hydrogen Technology Advisory Committee (HTAC), comprised of experts from industry, universities, and environmental groups, will continue to function in its role as a technical advisor to the Secretary. The Program Management and Operations Plan will describe how each of these organizational units will work together to ensure that the Department conducts its hydrogen research in a coordinated, focused, and efficient manner.

International cooperation and collaboration will also be important to efficiently achieve national hydrogen and fuel cell technology program goals. The Secretary has led the creation of an "International Partnership for the Hydrogen Economy" that establishes cooperative R&D efforts, common codes and standards, and the sharing of information necessary to develop a hydrogen fueling infrastructure.

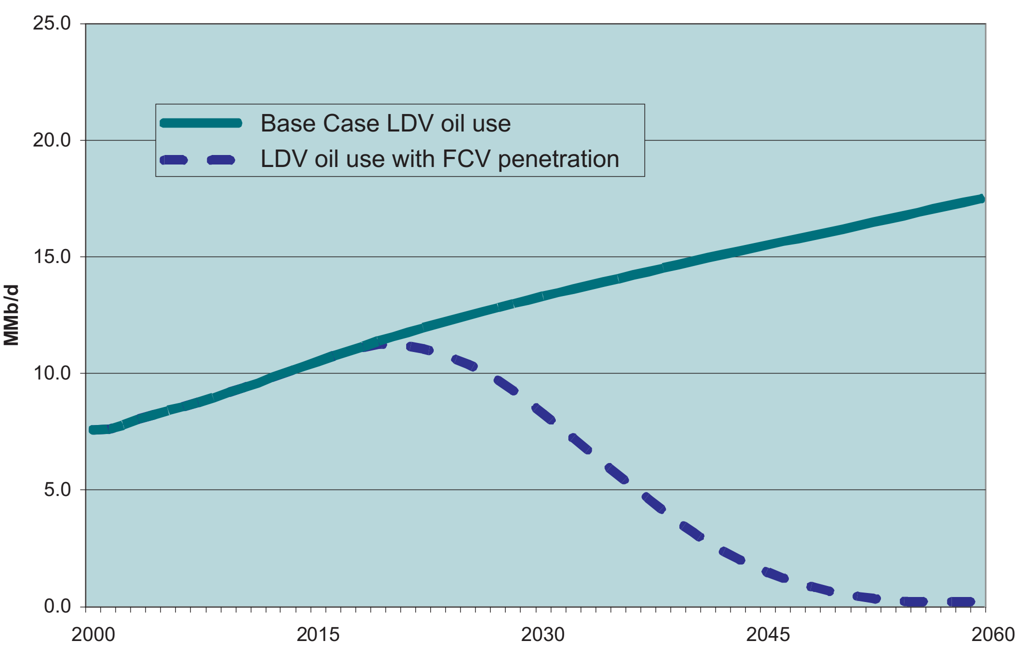
5. Potential Impacts on Oil Use and Greenhouse Gas Emissions

Expanded use of domestic resources to produce hydrogen will strengthen U.S. energy security and improve environmental quality. Achievement of hydrogen technology goals will pave the way for hydrogen's rapid growth as an energy carrier over the next several decades. The full extent of life-cycle cost and energy and environmental impacts will become clearer as technology development and validation progresses on the various production, conversion and distribution options. To illustrate the range of impacts, the remainder of this section presents some market penetration scenarios. Over the next two decades, conservation and high-efficiency petroleum-based vehicles can provide the greatest impact on reducing oil use and emissions.

Transportation

Every day, eight million barrels of oil are required to fuel over 200 million vehicles that constitute our light-duty transportation fleet. The U.S. imports over half of the oil it consumes. Fuel cell vehicles could provide more than twice the efficiency of conventional vehicles and have the potential to reduce our dependence on oil while substantially

Figure 10. Oil Use by Light Duty Vehicles



By 2040, light-duty vehicle oil consumption may be reduced by over 11 million barrels per day using hydrogen fuel cell vehicles.[6]

[5] The energy efficiency assumed for FCVs relative to conventional vehicles is 2.25 in 2018 and 2020, 2.5 in 2030 and 2040 and 3.0 beginning in 2050 with linear interpolation used for intervening years (assumes average new light duty vehicle fuel economy of 24.3 mpg for baseline vehicles).

[6] The penetration rate of FCVs in LDV sales is assumed to be 4% in 2018, 27% in 2020, 78% in 2030 and 100% by 2038 with linear interpolation for intervening years.

reducing emissions of air pollutants and greenhouse gases[5]. Figures 10 and 11 provide an example of the dramatic decrease in oil use and associated carbon emissions that could be realized by using hydrogen fuel cell vehicles.

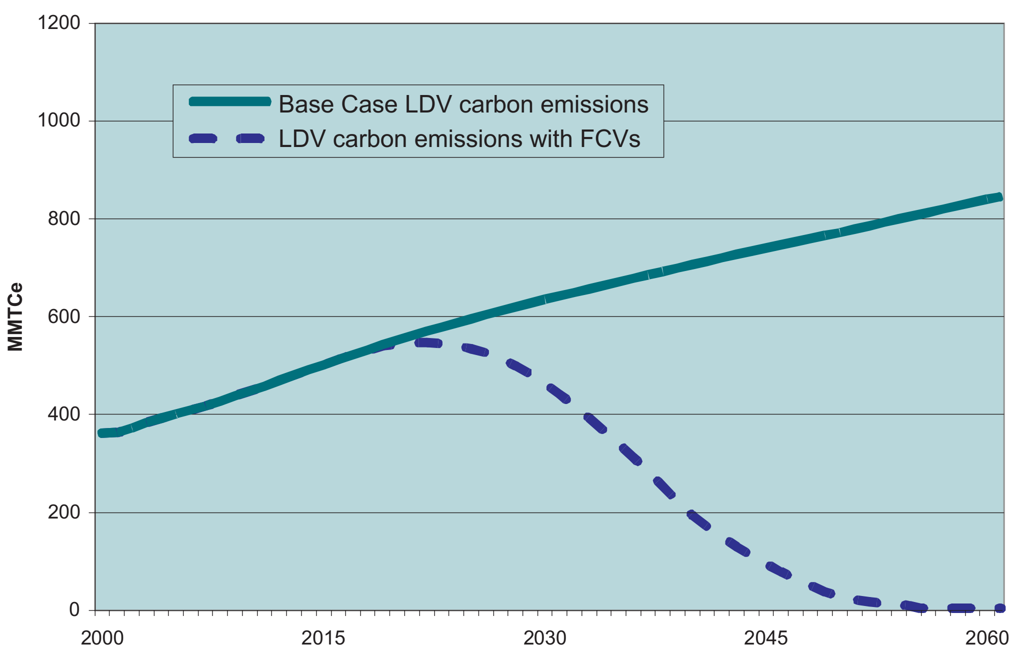
Stationary Power

Hydrogen can be used in stationary fuel cells, engines and turbines to produce power and heat. In order to meet our growing electrical demands, it is estimated that electricity generation will have to increase by 2% per year[7]. At this rate, 1.5 trillion kWh of additional electricity generation capacity will be needed by 2020. As an example, if 10 million tons of hydrogen per year were used to provide 150 billion kWh of the nation's electricity (just 10% of the added generation), 20 million tons per year of carbon dioxide emissions could be avoided assuming the hydrogen is produced using renewables, nuclear, or fossil fuels with carbon capture and sequestration. Additional use of hydrogen technologies may be expected given aging infrastructure, requirements for reliable premium power, and market deregulation.

Energy Diversity

Hydrogen can be supplied in large quantities from domestic fossil, nuclear and renewable resources. Hydrogen and fuel cells can increase the utilization of and establish a viable transportation market for nuclear energy, large domestic coal supplies, and renewables. Table 1 shows that our nation possesses the necessary resources to produce large quantities of hydrogen and begins to establish a picture of the required footprint for these production facilities.

Figure 12. Carbon Emissions with Fuel Cells



By 2040, light-duty vehicle carbon emissions may be reduced by more than 500 million metric tons of carbon equivalent each year using hydrogen fuel cell vehicles.[8]

[7] U.S. DOE, Energy Information Administration, Annual Energy Outlook 2002

[8] Hydrogen is produced from natural gas or zero carbon fuels. The percentage from natural gas is assumed to be 93% in 2018, 90% in 2020, 55% in 2030, 15% in 2040, and 0% by 2050.

Table 1. Hydrogen Production from Domestic Resources Summary

Examples of domestic resources that could be used to produce 40 million short tons of hydrogen to fuel 150 million vehicles (values shown are based on that resource being used to produce the full 40 million tons). The long-term strategy is to produce hydrogen from an array of diverse feedstocks. This analysis is only for perspective – currently 9 million short tons of industrial hydrogen are produced annually and 150 million vehicles is 75% of the light duty fleet. Note - The DOE Hydrogen Program is developing advanced technologies that could reduce these estimates of resource consumption and/or the footprint of these routes.

Resource	Needed for Hydrogen[a]	Availability	Current Consumption	Consumption with Hydrogen Production (factor times current)	Construction/ Footprint Required
Reforming and/or Partial Oxidation[b]					
Natural Gas	95 million tons/year	28 billion tons (technically recoverable as of 1/2000)	475 million tons/year	1.2	400 dedicated hydrogen plants (100 MMSCF of hydrogen per day)
Biomass	400-800 million tons/year	800 million tons/year of biomass residue and waste, plus 300 million tons/year of dedicated crops[c]	200 million tons/year (3 quads for heat, power & electricity)	2-4	400-600 dedicated hydrogen plants
Coal	310 million tons/year	126 billion tons (recoverable bituminous coal)	1100 million tons/year (all grades)	1.3	280 dedicated hydrogen plants
Water Electrolysis[d]					
Wind	555 GW_e	3250 GW_e	4 GW_e	140	Available capacity of North Dakota (Class 3 and above)
Solar	740 GW_e	SW U.S.: 2,300 kWh/m^2-year	<1 GW_e	>740 times current	3750 sq. miles (approx. footprint of White Sands Missile Range, NM)
Nuclear	216 GW_e	n/a	98 GW_e	3.2	200 dedicated plants (1-1.2 GW_e)
Thermo-Chemical					
Nuclear	300 GW_{th}	n/a	0 GW	n/a	125 dedicated plants (2.4 GW_{th})

a Examples of domestic resources that could be used to produce the 40 million short tons of hydrogen needed to fuel 150 million vehicles (values shown are based on that resource being used to produce the full 40 million tons of hydrogen); assumes a 2.2x improvement in efficiency over 27.5 mpg baseline fuel economy using hydrogen fueled vehicles. (Note: all table measurements are in short tons.)

b Calculations were made for the exclusive production of the amount of hydrogen requested. However, these systems can be configured to capture heat and generate both heat and electricity in combined heat and power (CHP) systems.

c Includes only that biomass not currently used for food, feed and fiber products.

d Other renewable power generation technologies can also serve as a resource for water electrolysis. For example, geothermal could provide 11 million tons of hydrogen per year (up to 68 million tons of hydrogen if estimates of undiscovered accessible resources are considered). Undeveloped hydropower resources and upgrades to existing hydroelectric plants could supply an additional 15 million tons of hydrogen per year.

Sources: U.S. DOE, Energy Information Administration, Annual Energy Outlook 2002.

Arthur D. Little (2001). "Aggressive Growth in the Use of Bio-derived Energy and Products in the United States by 2010."

D. Gray and G. Tomlinson (2002). "Hydrogen from Coal." Mitretek Technical Paper. MTR2002-31.

6. Next Steps

✦ Coordinate the detailed multi-year RD&D plans and priorities for hydrogen and related technology development efforts in the Department to make them consistent with this planning document and the National Academies' study requested by DOE.

✦ To strengthen coordination within DOE, establish a working group composed of representatives from the Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy, Science and Technology; Science; Management, Budget, Evaluation/CFO; and Policy and International Affairs (in an oversight capacity). This working group should meet periodically to perform the following functions:
- Evaluate the Department's progress in meeting milestones and performance goals in hydrogen and related activities.
- Strengthen information exchange on technical developments.
- Help ensure continued close integration among the Department's hydrogen-related activities (e.g., budgeting, execution, evaluation, and reporting).
- Provide suggestions for improving management and technical performance.
- Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways.

✦ Prepare a Program Management and Operations Plan to provide further detail on the overall management and integration of the Department's Hydrogen Program, including reporting requirements, oversight/advisory roles and responsibilities, and baseline requirements, cost, and schedule.

✦ Reflect the importance of the following activities in the Department's out-year planning and budgeting:

- Exploratory research in hydrogen storage, production, and fuel cell cost and durability.
- Hydrogen delivery and development of infrastructure (these activities need to be closely coordinated with the Department of Transportation (DOT), which is responsible for efforts to ensure the safety of the hydrogen delivery system).
- Economic and systems analyses for determining and mitigating investment risks associated with hydrogen infrastructure and related technologies (e.g., fuel cell systems engineering and manufacturing plants).

✦ Increase the energy industry participation in the initiative, in recognition of the industry's key role in energy production and delivery infrastructures. Greater energy and utility industry participation is vital to a successful transition to a hydrogen economy.

✦ Strengthen and continue existing interagency coordination efforts to ensure that Federal investments in hydrogen energy development are leveraged to the maximum extent. The following agencies are participating with the Department of Energy in the Hydrogen Interagency Research and Development Task Force to discuss national hydrogen and related activities: Departments of Defense, Commerce, Transportation, Agriculture, and State; Office of Management and Budget; Office of Science and Technology Policy; National Science Foundation; National Institutes of Standards and Technology; Environmental Protection Agency; and National Aeronautics and Space Administration.

- Strengthen international cooperation on hydrogen-related research, development, and demonstration programs and on the development of interoperable codes and standards through the International Partnership for the Hydrogen Economy.
- Be aware of the nation's regulatory framework of energy, economic, and environmental policies at the federal, state, and local levels, and work with the appropriate agencies to coordinate the timing of policy instruments and regulatory actions to allow technology to meet market requirements.

Appendices

A. Hydrogen Production Pathways

B. Glossary/Acronyms

C. Contacts, Resources and Weblinks

Appendix A. Hydrogen Production Pathways

Table A-1 summarizes a multitude of hydrogen production and delivery options. The large number of options is one of the key advantages to hydrogen as an energy carrier.

Table A-1. Summary of Production Options

<table>
<tr><th>Raw Feedstock Options</th><th>Typical Processed Feedstock</th><th>Production Process Options</th><th>Process Energy Source Options</th><th>Production Strategy Options</th><th>Delivery Options</th></tr>
<tr><td>Fossil Fuels
♦ Coal
♦ Natural gas
♦ Oil</td><td>♦ Syngas
♦ Gasoline
♦ Diesel fuel
♦ Methanol
♦ Ammonia
♦ Direct use of raw stock</td><td rowspan="4">Thermal
♦ Reforming
- Steam reforming
- Partial oxidation
♦ Gasification
♦ Pyrolysis

Electrochemical
♦ Electrolysis
♦ Photoelectro-chemical

Biological
♦ Photo-biological
♦ Aerobic fermentation
♦ Anaerobic fermentation</td><td rowspan="4">Thermal
♦ Fossil
♦ Renewable
♦ Nuclear

Electricity
♦ Fossil
♦ Renewable
♦ Nuclear

Photolytic
♦ Solar</td><td rowspan="4">Distributed
♦ Fueling stations
♦ Individual buildings
♦ On-board

Semi-Distributed
♦ Market-Centered

Central
♦ Resource-Centered</td><td rowspan="4">Hydrogen
♦ Gas pipeline
♦ Gas – rail or barge
♦ Gas – trucked
♦ Gas tube trailors
♦ Liquid – trucked
♦ Liquid – rail or barge
♦ Hydrides
♦ Other (e.g., carbon nanotubes)

Other Gaseous Carriers
♦ Natural gas
♦ Ammonia

Liquid Carriers
♦ Ethanol
♦ Methanol
♦ Other organic liquids</td></tr>
<tr><td>Biomass
♦ Lignocellulose
♦ Starch
♦ Vegetable oils
♦ Black liquor</td><td>♦ Ethanol
♦ Methanol
♦ Biodiesel
♦ Biogas
♦ Sugars
♦ Direct use of raw stock</td></tr>
<tr><td>Waste Material
♦ Municipal solid waste
♦ Stack gases
♦ Waste water</td><td>♦ Direct use of raw stock</td></tr>
<tr><td>Water</td><td>♦ Direct use of raw stock</td></tr>
</table>

The National Energy Policy calls for a diversity of domestic energy sources for national security and increased supply capability for our energy needs. Hydrogen can be produced from a variety of feedstocks including fossil fuels, nuclear, and renewable energy sources.

There are numerous hydrogen production processing options that can each be used for several of the feedstock options. Hydrogen can be produced in large central facilities and distributed to the point of use. It can be produced in a semi-distributed fashion near the larger market centers such as urban centers and urban corridors, or it can be produced directly at the point of use such as existing transportation refueling stations or even in a home or commercial building. It can be produced from hydrogen-rich liquid fuels in on-board reformers. It can be produced in a Vision 21 energy complex such as at an

Integrated Gasification Combined Cycle coal plant that could provide power, hydrogen, liquid fuels, and chemicals all at one site.

One can also envision a biorefinery using a biomass feedstock gasification operation (very similar to the coal energy complex example) based on wood residues, crop residues such as corn stover, or an energy crop such as switchgrass. Finally, hydrogen can be delivered from a central or semi-distributed production operation through a variety of means including new dedicated hydrogen pipelines, liquid transport via truck or rail, or possibly using new solid hydrides as a result of successful research.

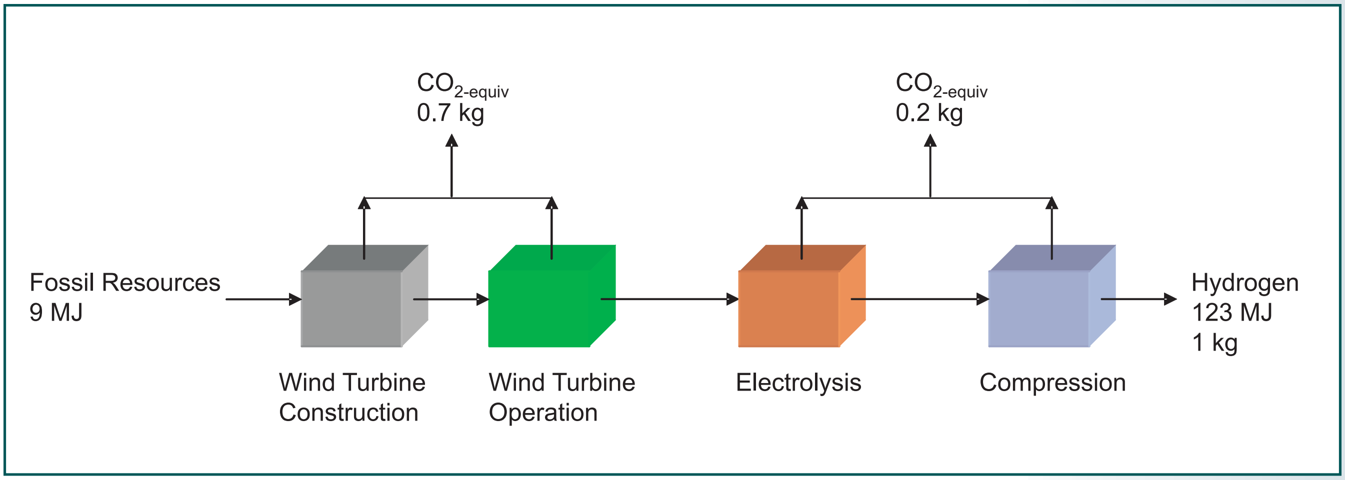
This variety of options for domestic feedstock, production, and delivery provides the diversity that the National Energy Policy requires. However, there are trade-offs within the matrix of options. Some options are better suited for central production, while others are better suited for distributed production. The cost and energy needed to distribute and deliver hydrogen is a major contributing factor because of its relatively low energy density. Further research and development will be needed to achieve competitive costs for hydrogen compared with conventional energy systems in use in the marketplace today; however, some options are closing in on cost goals.

Sufficient feedstock supply for hydrogen production is another area of concern. Table 1 (shown in Section 5, Program Benefits) summarizes recently compiled information on domestic resource availability. The table shows the resources that would be required from several key production routes to produce 40 million tons of hydrogen/year (enough to fuel 75% of the current light-duty vehicles on the road today, assuming fuel cells are used and are twice as efficient as today's conventional internal combustion engines running on gasoline). The calculations for most of the production routes shown in the table are based on current commercial or demonstrated technologies. Advanced production technologies are being developed within the DOE Hydrogen Program that could improve process efficiencies, resulting in reduced resource needs.

In the end, it is highly likely that hydrogen will be produced and delivered utilizing several feedstocks, processing options, and delivery options at a variety of scales ranging from large central production to very small local production. One of the tasks at hand is to develop a better understanding of the options available, the current and potential costs and energy efficiencies of these options, and the trade-offs each represent. From this understanding, we will further and continuously refine the DOE research and development plan for hydrogen production and delivery to ensure viable, cost-effective options become available for both the short term and long term.

Figures A-1 to A-4 present resource flows, fossil-fuel consumption, and greenhouse gas emissions for several potential hydrogen production pathways. Continuing analysis will be conducted to revise, refine, and expand these preliminary calculations. For those pathways that involve centralized production, transportation and delivery add significantly to energy requirements and emissions of air pollutants and greenhouse gases. Since there is a large variety of methods and distances involved in distribution and transport, no attempt has been made to quantify this aspect. Also, it is important to note that the fossil-fuel consumption and resulting emissions shown are highly dependent on the technology and equipment selected. Several advanced technologies are being developed for some production routes that could result in a 10-20% increase in system efficiency and similar decreases in emissions.

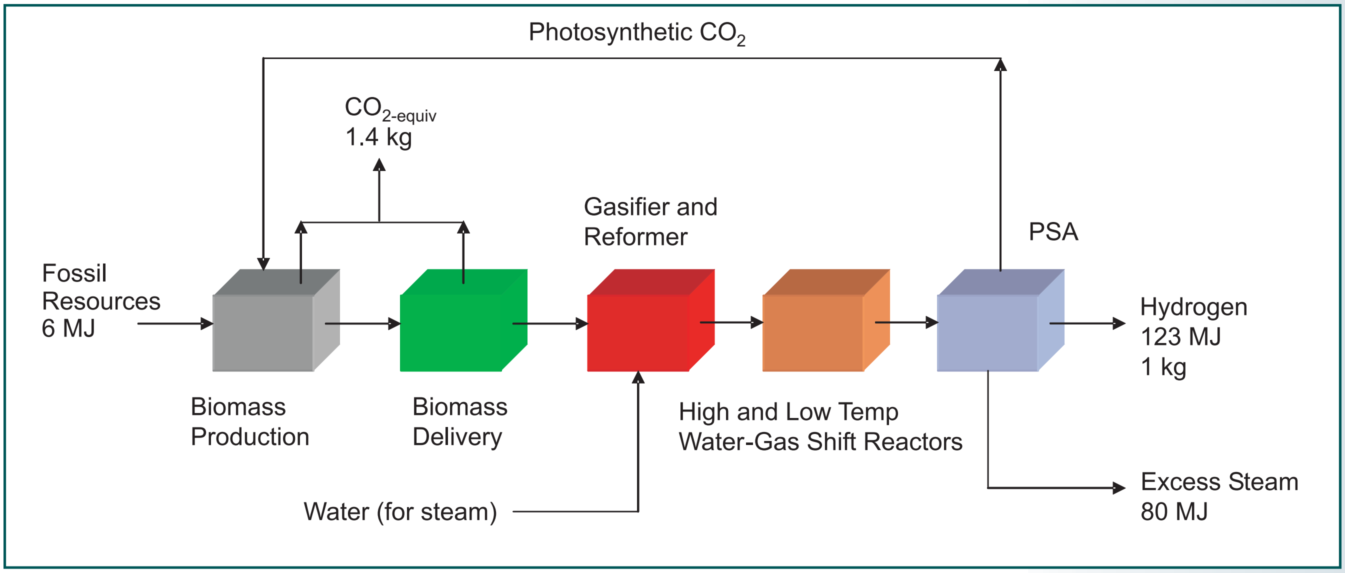
Figure A-1. Distributed Hydrogen Production from Wind Electrolysis



Wind power is currently the most cost-effective renewable power technology. In conjunction with water electrolysis, wind can provide hydrogen at the consumer site with few emissions and with very low consumption of fossil resources. The CO_2-equivalent emissions from this process are associated with the manufacture and installation of the wind turbine (steel for construction and concrete for installation), and with the electricity needed to compress the hydrogen for on-site storage.

Source: Spath, P.L.; Mann, M.K. (2001). "Life Cycle Assessment - An Environmental Comparison of Hydrogen Production from Steam Methane Reforming versus Wind Electrolysis." The 12th National Hydrogen Association Meeting. March 6-8, Washington, D.C.

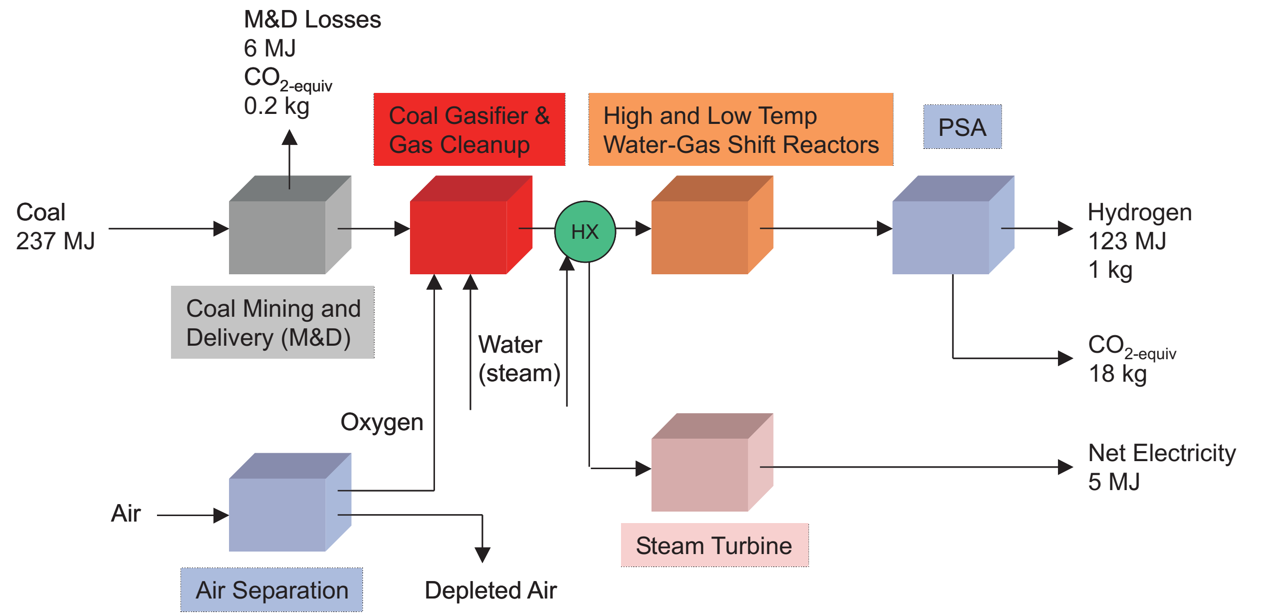
Figure A-2. Hydrogen Production from Biomass Gasification.



Biomass-derived hydrogen is another low-CO_2 impact process for the production of hydrogen. Biomass (wood, agricultural residues, or energy crops) absorbs as much CO_2 from the atmosphere during growth as is released during gasification. Fossil resources are only needed for certain operations such as planting, cultivating, and collecting the biomass. In this diagram, we show the CO_2 being recycled by photosynthesis into additional biomass. It would also be possible to capture and sequester the CO_2 from the PSA unit (as discussed in the SMR case in Figure B-1) to derive additional benefits through a hydrogen process with significantly negative CO_2 emissions.

Source: Mann, M.K.; Spath, P.L. (1997). Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System. National Renewable Energy Laboratory, Golden, CO, TP-430-23076.

Figure A-3. Energy Requirements and GHG Emissions – Centralized Hydrogen Production from Coal Gasification



Based on bituminous coal

Domestic coal can be a major source of hydrogen in the near to mid-term. In the long-term, RD&D will improve technology that will lower the cost to produce hydrogen from coal, and also enable sequestration of carbon. Figure B-4 represents a process to produce hydrogen based on conventional technology. The process assumes that an entrained, quench gasification system with conventional acid removal (gas cleanup) and pressure swing adsorption (PSA) for hydrogen recovery is used.

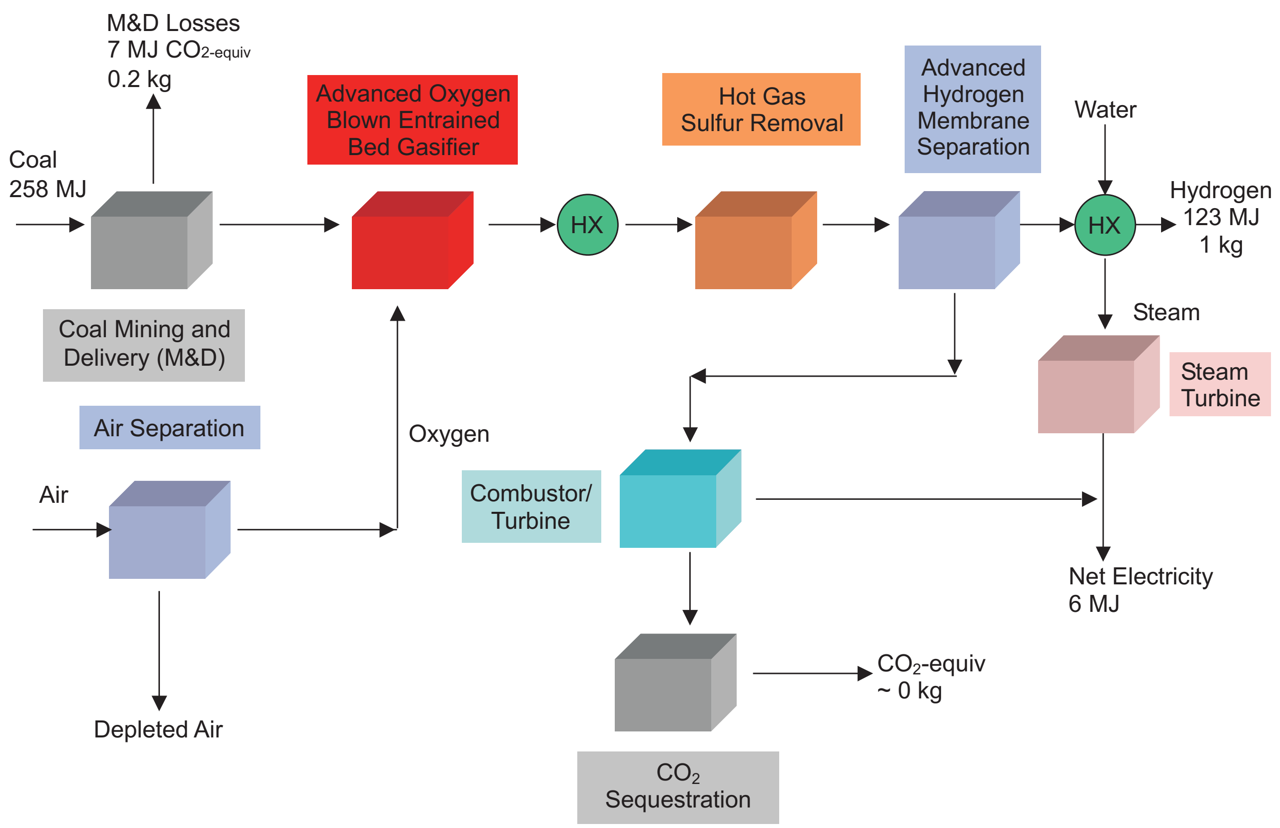
Sources: Spath, P.L.; Amos, W.A. (2000). "Hydrogen Production from Western Coal Including CO_2 Sequestration and Coalbed Methane Recovery: Economics, CO_2 Emissions, and Energy Balance." Advances in Hydrogen Energy. New York: Plenum Publishers, pp. 17-30.

Spath, P.; Amos, W.; Chambers, H.; Revay Madden, D.; Smith, D.; Shelton, W. (1999). "Technoeconomic Analysis of Hydrogen Production from Western Coal Augmented with CO_2 Sequestration and Coalbed Methane." 218th ACS National Meeting. New Orleans, Louisiana. August 22 - 26.

D. Gray and G. Tomlinson (2002). Hydrogen From Coal. MTR 2002-31. Mitretek Systems, Falls Church, VA.

U.S. Department of Energy, Fossil Energy Program: Hydrogen Program Plan.

Figure A-4. Energy Requirements and GHG Emissions – Centralized Hydrogen Production from Advanced Coal Gasification with Sequestration



Based on bituminous coal

This figure represents a process for hydrogen production from coal that uses advanced gasification technology, advanced membrane technology for hydrogen separation and carbon dioxide removal, and carbon sequestration. In this configuration, advanced two-stage gasification with hot gas cleanup is used in combination with a ceramic membrane system operating at nearly 600°C that is capable of shifting and separating hydrogen from clean synthesis gas. It is assumed that 90 percent of the synthesis gas is converted in this membrane system. The hydrogen produced is separated at low pressure and must be compressed. The remaining synthesis gas, containing mostly carbon dioxide with some carbon monoxide and hydrogen, is then combusted with oxygen in a gas turbine to provide power for the plant. Oxygen is used so that a concentrated stream of carbon dioxide is produced for sequestration. Heat is recovered from both the gas turbine exit gas and from the hot hydrogen in heat recovery steam generators (HRSGs) where the steam produced is sent to a steam turbine to provide additional power. The excess power produced is then sold. Even more advanced concepts are planned to be developed toward 2020 which would employ advanced solid oxide fuel cells in addition to the other technology advancements previously discussed. These hydrogen and electricity co-production plants could provide significant additional reductions in the cost of hydrogen.

Sources: D. Gray and G. Tomlinson (2002). Hydrogen From Coal. MTR 2002-31. Mitretek Systems, Falls Church, VA.

U.S. Department of Energy, Fossil Energy Program: Hydrogen Program Plan.

Appendix B. Glossary/Acronyms

AC .... Alternating Current
ANSI .... American National Standards Institute
ASME .... American Society of Mechanical Engineers
ATS .... Advanced Turbine Systems
CHP .... Combined Heat and Power
CO .... Carbon Monoxide
CO_2 .... Carbon Dioxide
CSA .... Canadian Standards Association
DC .... Direct Current
DOD .... U.S. Department of Defense
DOE .... U.S. Department of Energy
DOT .... U.S. Department of Transportation
EPA .... U.S. Environmental Protection Agency
FY .... Fiscal Year
ICC .... International Code Council
IEC .... Independent Electrical Contractors
IEEE .... Institute of Electrical and Electronic Engineers
ITM .... Ion Transport Membrane
Electrolyzer ... A device that uses electricity to produce hydrogen from water
EERE .... Energy Efficiency and Renewable Energy
FE .... Fossil Energy
GGE .... Gallon of Gasoline Equivalent
ISO .... International Standards Organization
kW .... Kilowatt
MMT .... Million Metric Tons
MMTCE ...... Million Metric Tons Carbon Equivalent
NASA .... National Aeronautics and Space Administration
NE .... Nuclear Energy
NIST .... National Institute of Standards and Technology
NO_X .... Nitrogen Oxides
NSF .... National Science Foundation
PEM .... Polymer Electrolyte Membrane
PSI .... Pounds per Square Inch
QC .... Quality Control
R&D .... Research and Development
RD&D .... Research, Development and Demonstration
RFP .... Request for Proposal
SAE .... Society of Automotive Engineers
SECA .... Solid State Energy Conversion Alliance
SMR .... Steam Methane Reformer
SOFC .... Solid Oxide Fuel Cell
SOX............. Sulfur Oxide
UL .... Underwriters Laboratories, Inc.
USDA.......... United States Department of Agriculture
V .... Volt
VOC .... Volatile Organic Compound

Appendix C. Contacts, Resources, and Weblinks

Posture Plan Team: Core Members

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www.eere.energy.gov/hydrogenandfuelcells

National Hydrogen Energy Roadmap
November 2002
www.eere.doe.gov/hydrogenandfuelcells

Basic Research Needs for the Hydrogen Economy: Report on the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use
May 13-15, 2003
www.sc.doe.gov/bes/hydrogen.pdf

National Energy Policy
May 2002
www.whitehouse.gov/energy

Department of Energy FY2005 Budget Request
http://www.mbe.doe.gov/budget/05budget/index.htm

Web Sites of Relevant DOE Offices

Office of Energy Efficiency and Renewable Energy
www.eere.energy.gov

FreedomCAR and Vehicle Technologies Program
www.eere.energy.gov/vehicle.html

Hydrogen, Fuel Cells and Infrastructure Technologies Program
www.eere.energy.gov/hydrogenandfuelcells

Office of Fossil Energy
www.fe.doe.gov

Office of Nuclear Energy, Science, and Technology
www.ne.doe.gov

Office of Science
www.science.doe.gov

Solid State Energy Conversion Alliance
www.seca.doe.gov