Hydrogen Posture Plan

An Integrated Research, Development and Demonstration Plan

December 2006

United States Department of Energy

United States Department of Transportation

Foreword

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

To address these challenges, the President's National Energy Policy, the Energy Policy Act of 2005, and the U.S. Department of Energy (DOE) Strategic Plan call for expanding the development of diverse domestic energy supplies. In 2006, the President announced the Advanced Energy Initiative (AEI).[1] The AEI accelerates research on technologies having the potential to reduce near-term oil use in the transportation sector including advanced batteries for hybrid vehicles and cellulosic ethanol, and reinforces the President's Hydrogen Fuel Initiative, which aims to make hydrogen fuel cell vehicles and fueling stations available to consumers in the longer term. The AEI also supports research to reduce the costs of advanced electricity production technologies in the stationary sector such as clean coal, nuclear energy, solar photovoltaics, and wind energy.

The Hydrogen Fuel Initiative accelerates the pace of research and development on hydrogen production and delivery infrastructure technologies needed to support hydrogen-powered fuel cells for use in transportation and electricity generation. Working with industry, academia, and the national labs, the DOE developed a long-term plan for moving toward widespread implementation of hydrogen technologies — a solution that holds the potential to provide virtually limitless clean, safe, secure, affordable, and reliable energy from diverse domestic resources. Ultimately, hydrogen could become one of a diverse set of alternatives that will address the energy needs of the United States. To realize this goal, the Nation must develop and validate advanced hydrogen fuel cell and infrastructure technologies while continuing to promote complementary near-term energy efficiency and renewable energy solutions, such as ethanol and hybrid electric vehicles.

The 2006 Hydrogen Posture Plan satisfies Section 804 of the Energy Policy Act of 2005, which requires that the Secretary of Energy transmit to Congress a coordinated plan for the Department's hydrogen and fuel cell programs. This plan also updates the previous plan, issued in February 2004, for successfully integrating ongoing and future hydrogen research, development and demonstration (RD&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 transportation and stationary applications. A coordinated Hydrogen Program will improve the effectiveness and accountability of the government's RD&D activities and increase the Program's ability to achieve its goals. Activities by the Department of Transportation (DOT) and the DOE are included.

The policy assumptions implicit in the Hydrogen Posture Plan are:

- The program is focused on the research and development activities needed to overcome the barriers to making hydrogen and fuel cell technologies competitive with alternative technologies.
- Learning demonstrations will be used to measure progress; identify issues during real-world operation that will provide feedback to the R&D program; validate the performance, durability, and cost of the technologies; address systems engineering issues; enable the DOE to provide information to Congress and the public on the status of the technology; and educate the public, especially safety and code officials and first responders.

- Commercial demonstrations and market transformation will occur only when the performance and durability of the technologies are validated. The decision to commercialize rests entirely with the private sector. Automakers may decide to market a fuel cell vehicle in a different time frame (perhaps earlier, perhaps later) than the DOE validation activities might suggest.

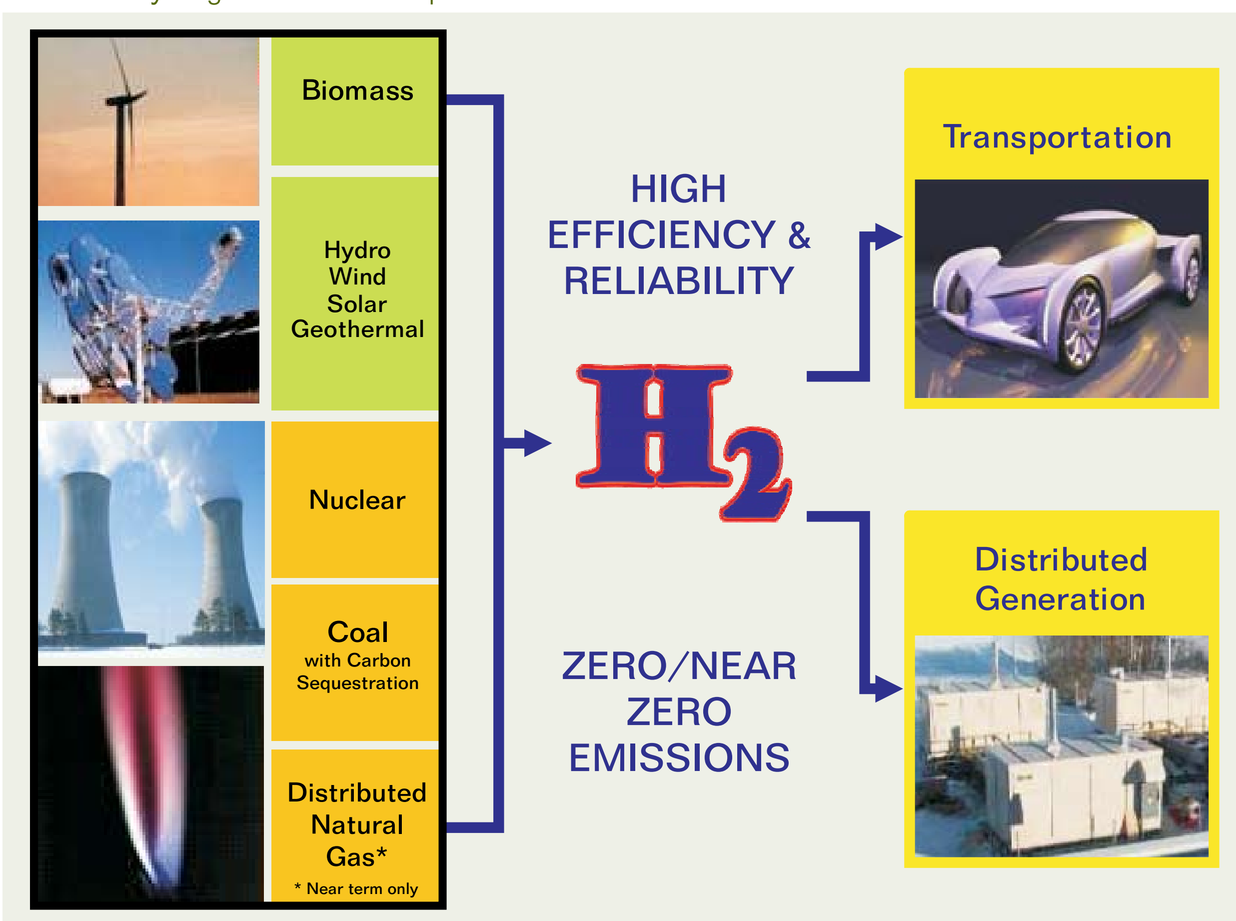
- When the performance and durability of the technologies are validated, the government may consider becoming an "early adopter" by purchasing or leasing hydrogen fuel cell vehicles and hydrogen refueling technologies to promote public acceptance of the technologies.

The goal of the Program is to develop hydrogen production, delivery, storage, and fuel cell technologies that enable the automobile and energy companies to opt for commercial availability of fuel cell vehicles and hydrogen fuel infrastructure by 2020.

Hydrogen has the long-term potential to reduce our dependence on foreign oil and lower carbon and criteria pollutant emissions from the transportation sector. In the near-term, gasoline-electric hybrid vehicles and biofuels (ethanol and biodiesel) offer excellent options for reducing oil use.

Ultimately, hydrogen from diverse domestic resources may be used in a clean, safe, reliable, and affordable manner in fuel cell vehicles, stationary, and portable power applications. Development of hydrogen, along with other domestic energy resources, 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.

Domestic Hydrogen Production Options



1. Introduction

Today, America is confronted by several 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
- Reducing air pollution and addressing concerns about climate change

The President's *National Energy Policy (NEP),* the Energy Policy Act of 2005, and the U.S. Department of Energy (DOE) *Strategic Plan* 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.

Positive Attributes of Hydrogen as an Energy Carrier

- Can be derived from diverse domestic resources (fossil, nuclear, renewable)
- Is 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 and from fossil fuel-based systems with carbon sequestration
- Can serve all sectors of the economy (transportation, power, industrial, and buildings)

As President Bush acknowledged in his January 2003 State of the Union address,[23] hydrogen has the potential to play a major role in America's future energy system. Hydrogen can be derived from a variety of domestically available energy sources (see several example pathways in Appendix B). It has a wide variety of applications, including fuel for automobiles and distributed and central electricity and thermal energy generation. DOE recognizes that the development of this abundant element as an "energy carrier," along with other alternative fuel options such as ethanol and efficient energy technologies such as plug-in hybrid vehicles, will help address national concerns about energy supply, security, and environmental protection. Congress expressed its support for the research, development, and demonstration (RD&D) of these technologies in the Energy Policy Act of 2005.

The DOE also recognizes that developing a hydrogen infrastructure will require a coordinated national effort and sustained activities by diverse public and private stakeholders. Today, hydrogen is commonly used in refineries and industrial applications to manufacture petrochemicals and fertilizers. The existing hydrogen production and distribution infrastructure is insufficient, however, to support widespread use of hydrogen as a transportation fuel. With the exception of pilot-scale research and development (R&D) projects and aerospace and rocket propulsion applications, the current hydrogen industry does not produce and distribute hydrogen as an energy carrier for transportation energy. Taking this step will require R&D to improve performance and lower costs for hydrogen production, delivery, and storage. R&D will also be required to develop low-cost, safe, technically viable fuel cell technologies that can be offered in consumer markets for automotive vehicles; commercial, residential, and industrial electric power generation; and portable power devices. Technology validation activities will be needed to measure progress and provide hands-on experience to safety and code officials. The President's Hydrogen Fuel Initiative accelerates funding in each of these areas.

"Critical Path" Technologies Necessary for Developing a Hydrogen Infrastructure

- More compact, lighter weight, lower cost, safe, and efficient storage systems
- Lower cost, more durable materials for advanced conversion technologies, especially fuel cells
- Lower cost methods for producing and delivering hydrogen
- Technologies for low cost carbon capture and containment for fossil-based hydrogen production (a separate DOE program coordinated with the Hydrogen Program)
- Designs and materials that maximize the safety of hydrogen use

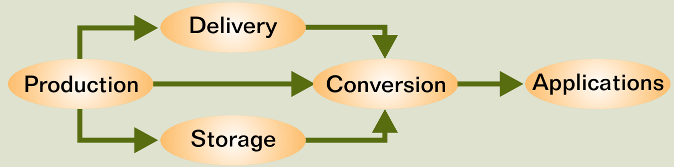
As a first step, the DOE facilitated a National Hydrogen Vision and Roadmap process and incorporated the opinions and viewpoints of a broad cross-section of stakeholders in two key documents: *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, and the *National Hydrogen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

The *Hydrogen Posture Plan* outlines the activities, milestones, and deliverables that DOE and DOT must pursue to develop hydrogen energy systems, the key elements of which are shown in Figure 1. Among the topics addressed are the schedules for developing and evaluating technologies to:

- Produce and deliver hydrogen using various domestic resources (e.g., distributed natural gas; coal using capture and sequestration of carbon dioxide; renewables including wind, solar, biomass, geothermal, and hydropower; and nuclear energy)
- Store hydrogen
- Convert hydrogen to useful energy through advanced fuel cells and other devices
- Continue developing advanced hybrid components and electric powertrain technologies for use in hybrid electric and fuel cell vehicles
- Conduct "learning" demonstrations to provide feedback to research programs, measure technology progress, and incorporate integrated system solutions

Education needs, safety, codes and standards, and systems analysis and integration are also major program elements. The Posture Plan also addresses the critical role of the FreedomCAR and Fuel Partnership, a government/industry partnership for the advancement of high-efficiency hydrogen-powered fuel cell vehicles and the infrastructure to support them, and the important role of future government policies in overcoming economic and institutional barriers to the development of a hydrogen infrastructure. The Posture Plan serves as the overarching guidance document for the Hydrogen Program.

Figure 1. Elements of a Hydrogen Energy Infrastructure



Production

- The production of hydrogen from fossil, nuclear, and renewable resources
- 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 containment of hydrogen for delivery, conversion, and use
- Involves tanks for both compressed gases and liquids
- Involves reversible and regenerable solid- and liquid-state systems, including metal and chemical hydrides

Conversion

- The use of hydrogen to generate 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 auxiliary and 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

2. Key Drivers for Developing Hydrogen as an Energy Carrier

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
- Economic competitiveness

Energy Security

Over one-half of the petroleum consumed in the United States is imported, and that percentage is expected to rise to 60% by 2025.[24] America's transportation sector relies almost exclusively on refined petroleum products, accounting for over two-thirds of the oil used.[25] Each day, over eight million barrels of oil[26] are required to fuel over 225 million vehicles[27] that constitute the U.S. light-duty transportation fleet. As shown in Figure 2, the gap between U.S. oil production and transportation oil needs is projected to grow, and the increase in the number of light-duty vehicles will account for most of that growth. 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.

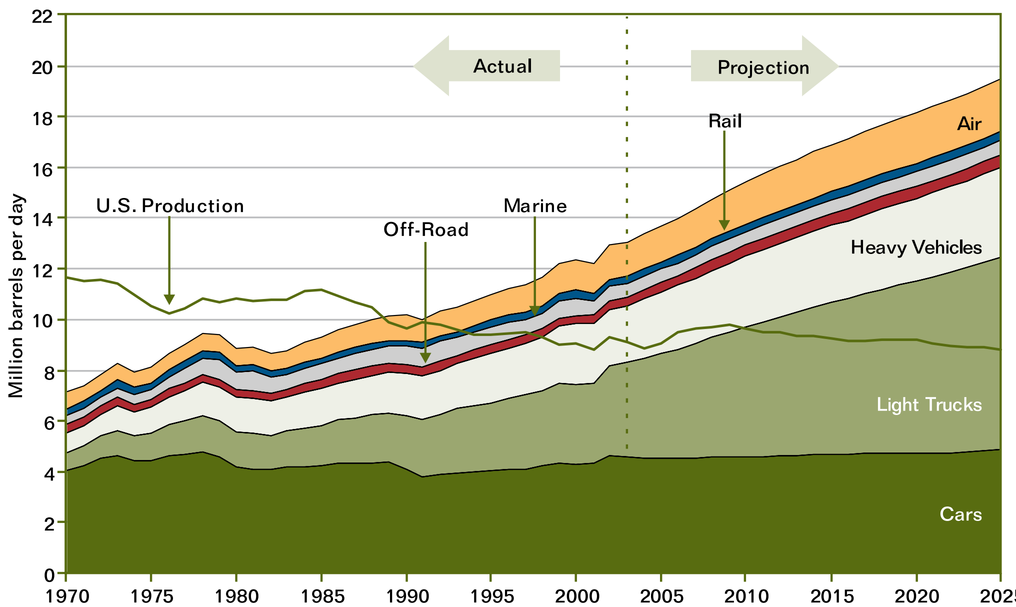
Hydrogen-powered fuel cell vehicles would not be dependent on foreign oil, because hydrogen can be produced almost entirely from diverse domestic sources of fossil, renewable and nuclear energy (see Appendix A for an example of domestic hydrogen production options and associated resource needs). Fuel cell vehicles (FCVs) could provide more than twice the efficiency of conventional vehicles and have the potential to reduce our dependence on oil while substantially reducing emissions of air pollutants and greenhouse gases.[28] Analysis conducted for the Government Performance and Results Act (GPRA) projects that oil savings could be 5.3 mbpd (million barrels per day) by 2050 assuming a 37% market penetration of light duty fuel cell vehicles.[29] Hydrogen's use as a major energy carrier, in addition to the introduction of other fuels, would also provide the United States with a more efficient and diversified energy infrastructure, with a variety of options for central and distributed fuel production and electric power generation.

Fuel Cells Offer Significant Improvements in Energy Efficiency and Emissions

Fuel cells represent a radically different approach to energy conversion, one that could replace conventional power generators like engines, turbines, and batteries in applications such as automobiles, power plants, and consumer electronics. Fuel cells, like batteries, directly convert chemical energy into electric power. 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 modular. 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[30]
- 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
- High energy density in a compact package for portable power applications

Figure 2. Growing U.S. Transportation Oil Gap

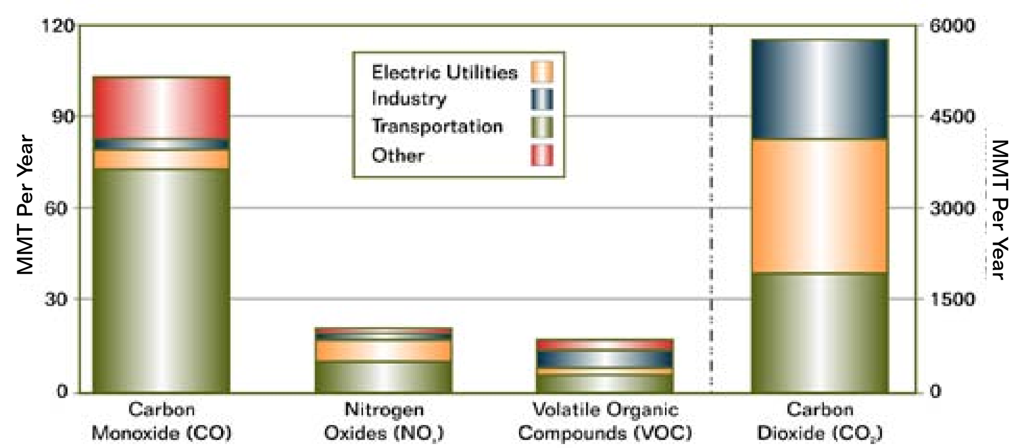


Source: Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 24*, (December 2004), ORNL-6973, http://cta.ornl.gov/cta/Publications/Reports/TEDB_Edition24_ORNL_6973.pdf and U.S. DOE, Energy Information Administration, *Annual Energy Outlook 2005: With Projections to 2025*, (February 2005), EIA-0383(2005), http://tonto.eia.doe.gov/FTPROOT/forecasting/0383(2005).pdf

Environmental Quality

Air quality is a major national concern. It has been estimated that about 50% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment.[31] 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 air quality goals and bringing their major metropolitan areas into alignment with the requirements of the Clean Air Act. The introduction of

Figure 3. Emissions from Fossil Fuel Combustion



Source: Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 25*, (2006), ORNL-6974, http://cta.ornl.gov/data/tedb25/Edition25_Full_Doc.pdf.

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. To meet our growing electrical demands, it is estimated that electricity generation will increase by 1.5% per year between now and 2030.[32] Hydrogen used in stationary fuel cells offers an opportunity to contribute to this growing electrical demand, and to decouple carbon dioxide emissions from power generation and use. For example, if 175 billion kWh of grid electricity (10% of the growth of the electric generation market in 2025) is replaced by fuel cells operating on hydrogen at 50% LHV efficiency, about 10.5 million tons of hydrogen would be needed. If this hydrogen were made from a non-carbon (e.g., solar or nuclear) or net-zero carbon (e.g., biomass or coal with carbon sequestration) source, then it could potentially displace about 27.5 million tons of carbon.[33]

Economic Competitiveness

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 $400 million annually[34] on hydrogen and fuel cell related programs. A subset of these programs — those that can directly contribute to the development of commercially-viable hydrogen fuel cell vehicles and associated infrastructure — comprise the Hydrogen Fuel Initiative. These programs have already begun to see significant funding increases as part of the President's Hydrogen Fuel Initiative. Other countries are increasing investment as well. The Japanese government is also investing heavily: the Ministry of Economy, Trade and Industry (METI) budget for fuel cell and hydrogen RD&D has grown from $107 million in 2001 to $324 million in 2005.[35] Japan has launched a joint government/industry demonstration of hydrogen fuel cell vehicles and stationary power generation facilities as well as ten hydrogen refueling stations with different hydrogen sources. Governments and industry in Canada, Europe, and Asia are also investing heavily in hydrogen research, development and demonstration.

International Partnership for the Hydrogen Economy: Membership

Australia	India
Brazil	Italy
Canada	Japan
China	New Zealand
European Commission	Norway
France	Republic of Korea
Germany	Russian Federation
Iceland	United Kingdom
	United States

The United States is striving to continue to be a global leader in hydrogen and fuel cell technology development and commercialization. To foster cooperation, the DOE and DOT facilitated the formation of the International Partnership for the Hydrogen Economy (IPHE), which held its inaugural IPHE Ministerial meeting in Washington, D.C. in November 2003. The IPHE, which includes 17 partners, provides a mechanism to organize, evaluate, and coordinate multinational research, development, and deployment programs that will advance the introduction of hydrogen infrastructure at a global scale. In the months since the Ministerial meeting, the IPHE Steering Committee has established an active IPHE Secretariat to address stakeholder involvement, policy coordination, project and event guidelines, technology collaboration, and market development issues. Initial meetings of the IPHE Implementation-Liaison Committee (ILC) focused on identifying the current hydrogen technology research, development, and demonstration activities of the IPHE partners and on examining approaches for focusing these activities with collaborative efforts. In 2005, collaborative projects were selected and prioritized. The ILC has also conducted a series of international research and development workshops, including a hydrogen storage workshop in Italy in June 2005, a hydrogen safety workshop in Italy in September 2005, and a renewable hydrogen production workshop in Spain in October 2005. More information on the IPHE can be found at http://www.iphe.net.

3. Development of Hydrogen as an Energy Carrier

Hydrogen technology 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 technology development, and thus industry's ability to make commercialization decisions on hydrogen-based transportation technologies. It is important to note that technology development is a necessary, but not sufficient, condition for commercialization. The *National Hydrogen Energy Roadmap* and the supporting hydrogen *Vision* provide a guide for the Department's hydrogen technology development efforts. The sections below summarize some of the highlights of the *Vision* and *Roadmap* and describe key elements of the technology development process.

Status of Hydrogen Today

Although hydrogen is the most abundant element in the universe, it does not naturally exist in its elemental form on Earth. Pure hydrogen 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 usable 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 significantly 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 are manufactured annually for use in these industries.[36] 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, high-efficiency production methods, and storage and delivery infrastructures compatible with automotive and distributed generation applications). As shown in Figure 4, there are a number of technical hurdles centered around cost, performance, and safety, that must be overcome in each area of the hydrogen energy infrastructure. 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* documents.

Technology Development and Market Transformation

Developing hydrogen as a major energy carrier will require a combination of technological breakthroughs, market acceptance, and large investments in 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 process might occur.

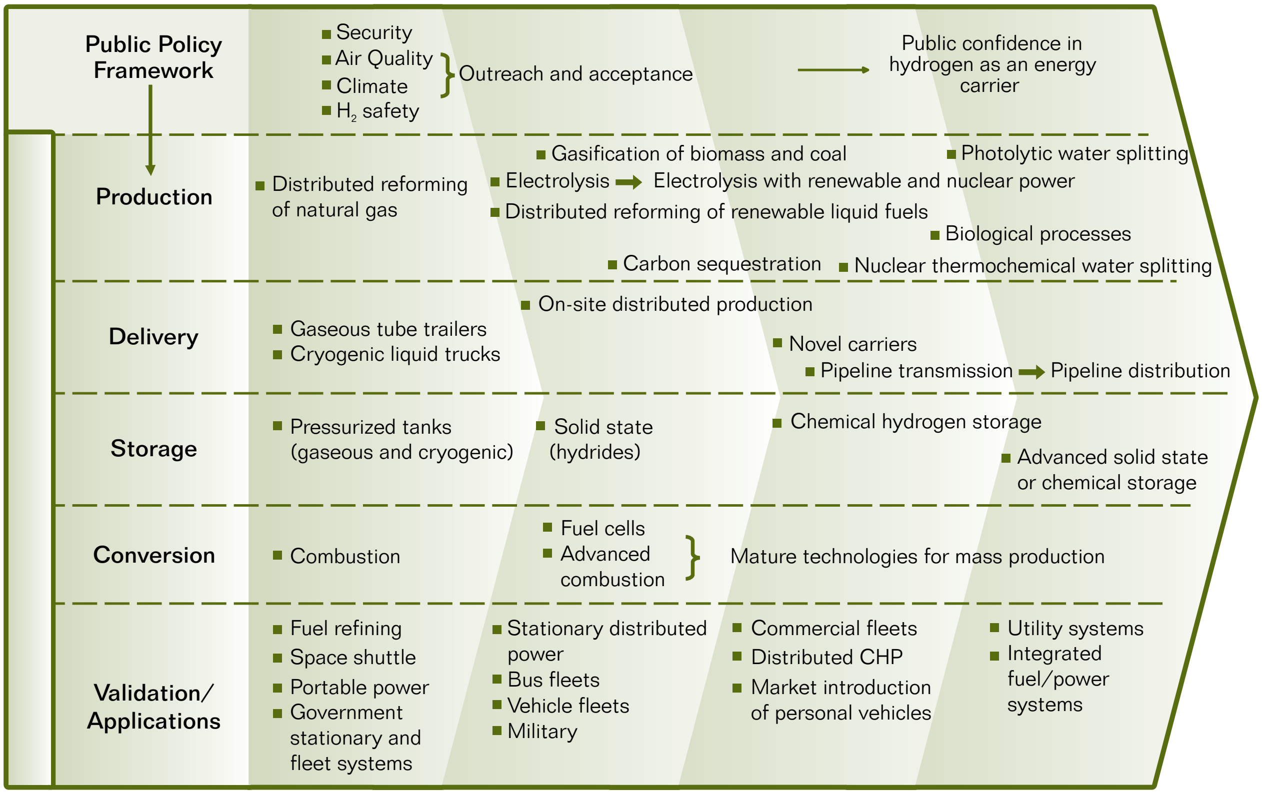
Figure 4. Hydrogen Energy System Elements and Challenges

Hydrogen Infrastructure Elements	Key Hurdles
PRODUCTION—Hydrogen could 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 could 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, renewable, and nuclear resources
DELIVERY—A national supply network would evolve over time to accommodate both centralized and distributed production facilities. Pipelines could be used to deliver hydrogen to high-demand areas. Trucks and other means could distribute hydrogen or liquid or solid hydrogen carriers to rural and other lower-demand areas.	◆ Lower-cost hydrogen transport technology ◆ Appropriate, uniform codes and standards ◆ Right-of-way for new delivery systems ◆ High investment risk of developing hydrogen delivery infrastructure
STORAGE—A selection of relatively lightweight, low-cost, and high capacity (low weight and volume) hydrogen storage devices would be available in a variety of sizes to meet different energy needs.	◆ Low cost, high capacity, lightweight, and low-volume hydrogen storage systems
CONVERSION—Fuel cells produced in high volumes would be cost-competitive, durable, and reliable and provide clear advantages in energy efficiency and emissions.	◆ Low cost, durable, and reliable fuel cells that can be mass-produced
TECHNOLOGY VALIDATION—Hydrogen could 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 of integrated systems that meet customer requirements ◆ Supportive public policies to stimulate infrastructure and market readiness
SAFETY, CODES AND STANDARDS—Model building codes that reference comprehensive equipment standards for hydrogen and fuel cell technologies for commercial and residential applications would be available for adoption by local jurisdictions.	◆ Fuel gas code that includes hydrogen ◆ Uniform safety standards for certification of fuel cell vehicles, stationary power facilities, and portable devices
EDUCATION—Businesses, government agencies, and the public may choose to use hydrogen to safely and conveniently power their vehicles; provide electricity and thermal energy to their factories, offices, and homes; and run portable electronic devices. Students in a variety of disciplines would be engaged in the development, advancement, and use of hydrogen and fuel cell technologies.	◆ Widespread understanding of, and confidence in, the safe use of hydrogen as an energy carrier ◆ Access to accurate, objective information about hydrogen and fuel cell technologies ◆ Education and training for emergency responders and code officials

As described in the National Academies' report on the hydrogen economy, in the near- to mid-term most hydrogen would likely be produced by technologies that do not require a new hydrogen delivery infrastructure (e.g., distributed reforming of natural gas and/or renewable liquid fuels such as ethanol, and electrolysis of water using electricity). As vehicle market penetration increases and research targets for the diverse hydrogen production and delivery technologies are met, these could help strengthen the business case for industry investment in large-scale centralized hydrogen production and delivery infrastructure. The economic viability of these different production pathways (examples of which are shown in Appendix B) will likely be 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 to provide adequate vehicle range. 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 delivery infrastructure can evolve along with the production and conversion technologies. The same infrastructure can be used for fossil-based, renewable- and nuclear-based hydrogen. Infrastructure may begin in small clusters and expand to regional, and ultimately national and international

Figure 5. Possible Evolution of Hydrogen Technologies



applications. More detailed economic analyses of the different production, distribution, storage, and conversion options will be essential.

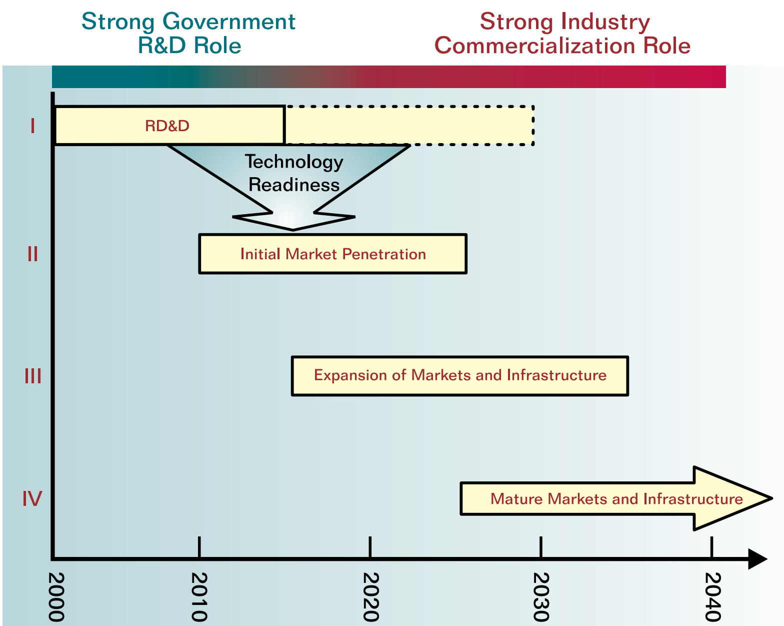
As shown in Figure 6, a hydrogen-based energy system will take significant time to develop and will require strong public and private partnerships. Currently, government and private organizations are researching, developing, and validating critical path technologies to meet customer requirements, ensure safety, and help establish a business case. Public education and codes and standards are being addressed concurrently with the research to overcome institutional barriers. This approach is designed to meet critical cost and performance goals, and enable industry commercialization decisions. Research would continue beyond this point to further support basic science and advanced hydrogen infrastructure technologies, especially for centralized, carbon-neutral hydrogen production pathways. Many market factors could influence industry commercialization decisions.

Although it is impossible to predict exactly how the market will evolve, it is likely that early applications for fuel cells will include niche markets with less sensitive price points, a high value proposition, and fewer technical barriers than fuel cells for passenger vehicles. Examples include fuel cells for portable consumer electronic devices, back-up power, small stationary power generation, and forklifts. These systems are less complicated, can have smaller power requirements, and do not face the same requirements for on-board hydrogen storage. Utilization of fuel cells in these types of applications may help resolve technical and institutional barriers, boost production volumes, and lower costs, which could help the technology evolve to a level of readiness adequate for hydrogen fuel cell vehicles and fueling infrastructure. Initial market penetration might also include larger vehicle and infrastructure validation where the government can foster further growth by playing the role of "early adopter" and by creating policies and incentives that further stimulate the market.

During market expansion, hydrogen could be produced by technologies that do not require an up-front investment in hydrogen delivery infrastructure. Instead, hydrogen might be produced in a "distributed" fashion at the refueling station (via on-site reforming of natural gas or renewable liquid fuels like ethanol or by distributed water electrolysis), or at nearby existing large hydrogen production plants and trucked to refueling sites. A fuel cell vehicle running on hydrogen produced from natural gas would produce 42% less net carbon emissions than a gasoline hybrid electric vehicle and 60% less than conventional internal combustion engine vehicles on a well-to-wheels basis.[37] However, the use of natural gas for production of hydrogen is not a viable long-term strategy because of concerns of limited supply and the demands of other sectors. As vehicle market penetration expands, greater industry investment could lead to development of large-scale centralized hydrogen production and delivery infrastructure. Government policies may be required to stimulate industry investment and market acceptance.

In a carbon-neutral energy future, hydrogen may offer one of a number of alternative fuel options to eliminate oil consumption in the transportation sector. When significant market penetration of these technologies is achieved, major national benefits in terms of energy security and improved environmental quality will result.

Figure 6. Possible Scenarios for Hydrogen Technology Development and Market Transformation



I. Technology Development
Research to meet technology performance and cost targets and establish technology readiness

II. Initial Market Penetration
Portable power and stationary/transport systems are validated; infrastructure investment begins with governmental policies

III. Expansion of Markets and Infrastructure
H_2 power and transport systems commercially available infrastructure business case realized

IV. Fully Developed Markets and Infrastructure
H_2 power and transport systems commercially available in all regions; national infrastructure