# Hydrogen Posture Plan

## An Integrated Research, Development and Demonstration Plan

December 2006

United States Department of Energy

United States Department of Transportation

# A National Commitment

In his 2003 State of the Union address, President Bush announced a hydrogen initiative to reverse America's growing dependence on foreign oil and improve the environment. The President urged the development of commercially viable fuel cells 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 George W. Bush
State of the Union Address, January 28, 2003

The National Academies' February 2004 report on the DOE Hydrogen Program concluded 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
The Hydrogen Economy: Opportunities,
Costs, Barriers, and R&D Needs
February 2004

In his speech for Earth Day 2005, DOE Secretary Samuel W. Bodman emphasized the importance of partnerships to fulfill the President's vision:

> *Numerous partnerships between all levels of government, the automotive and energy industries and their suppliers are making significant progress toward developing and deploying new hydrogen vehicles and the infrastructure to support them.*

— U.S. DOE Secretary Samuel W. Bodman
April 22, 2005

At the 2005 *DOE Hydrogen Program Review*, DOE Under Secretary David Garman remarked upon the need for teamwork among visionaries and pragmatists:

> *Imagining the hydrogen energy economy is easy enough for visionaries and dreamers, but ultimately it doesn't happen unless scientists and engineers overcome technical obstacles, entrepreneurs take risks, corporate boards commit capital, and consumers choose. What is remarkable about our efforts is that the visionaries and the pragmatists are working together, in close partnership, to make the hydrogen energy economy a reality.*

— David K. Garman, Under Secretary, U.S. DOE
May 23, 2005

When he signed the Energy Policy Act of 2005, President Bush reiterated his commitment to the hydrogen initiative and acknowledged the support of Congress:

> *The bill I sign today also includes strong support for hydrogen fuel technology. When hydrogen is used in a fuel cell, it can power consumer products from computers to cell phones to cars that emit pure water instead of exhaust fumes. I laid out a hydrogen fuel initiative, and I want to thank the members of Congress for adding to the momentum of this initiative through this energy bill.*

— President George W. Bush
Signing of the Energy Policy Act of 2005, August 8, 2005

# 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.

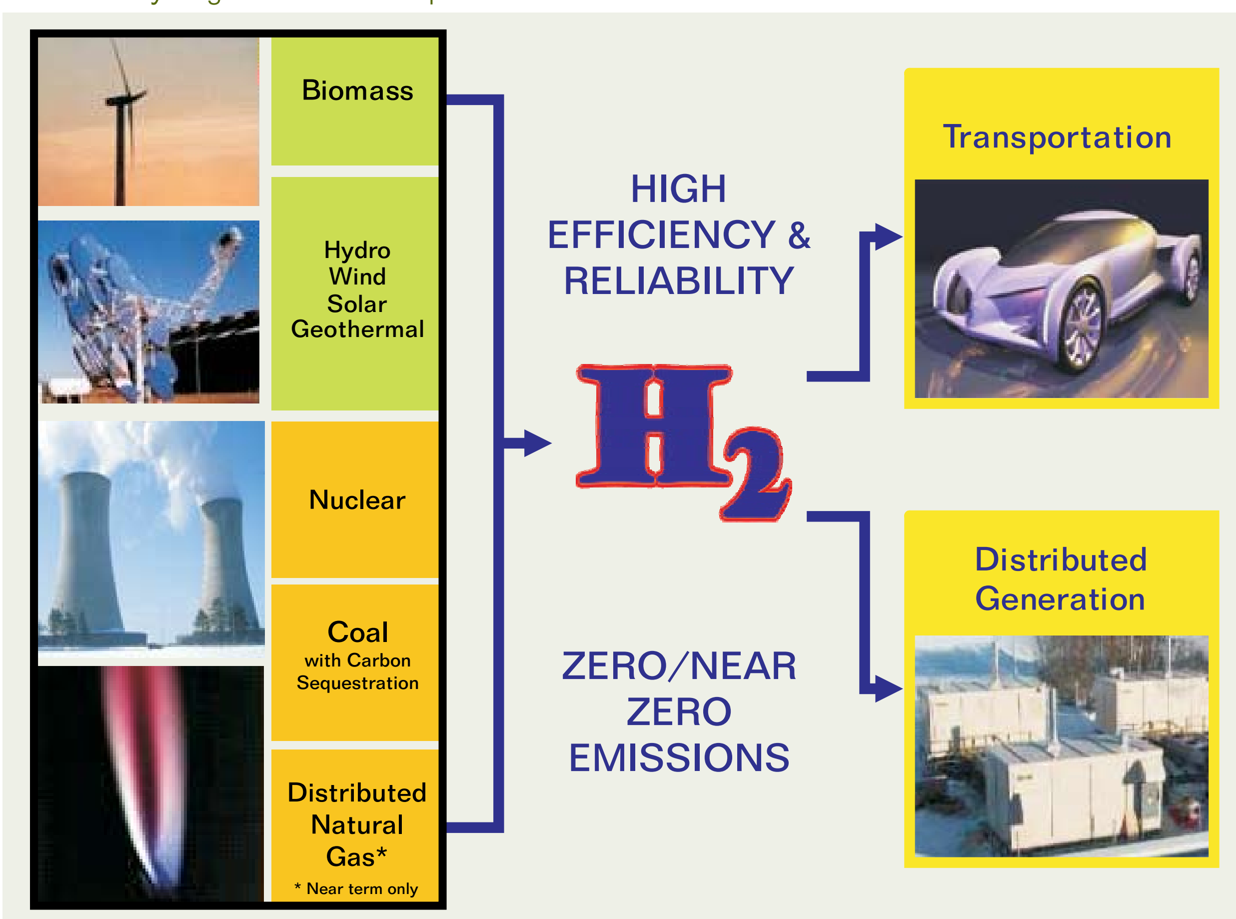
- When the performance and durability of the technologies are validated, the government may consider becoming an "early adopter" by purchasing or leasing hydrogen fuel cell vehicles and hydrogen refueling technologies to promote public acceptance of the technologies.

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



# Executive Summary

The Hydrogen Posture Plan was prepared by the U.S. Department of Energy (DOE) Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Science; Nuclear Energy, Science and Technology; and the U.S. Department of Transportation (DOT) to outline the activities, milestones, and deliverables that the Federal government plans to pursue to support the development of hydrogen-based energy systems. The Hydrogen Posture Plan integrates the planning and budgeting for program activities that will aid in this development. More specifically, this Plan outlines the DOE role in hydrogen energy research and development, in accordance with the National Hydrogen Energy Vision and Roadmap.[2, 3] The Plan lays the foundation for a coordinated response, including collaboration with the DOT, to the President's plan for accelerating implementation of hydrogen infrastructure and fuel cell technologies.

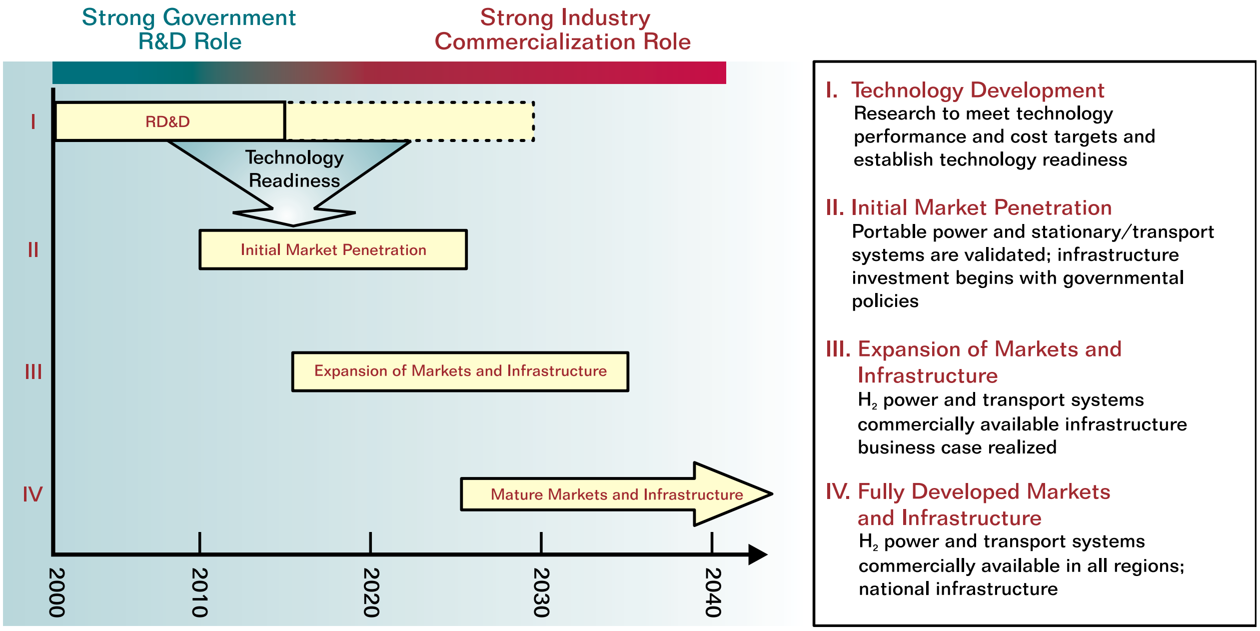
## *Key Points*

- Use of hydrogen as an energy carrier, together with other alternative domestic fuels and technologies, can enhance long-term energy security while mitigating the effects of air pollution and greenhouse gas emissions.
- Technical challenges to developing cost effective hydrogen technologies include lowering the cost of hydrogen production, delivery, storage, fuel cells, and end-use applications. Hydrogen systems require effective safety codes and standards, not only to ensure that these systems are safe, but to help define design standards for future hydrogen vehicles and infrastructure. In addition, education and outreach are vital to raise awareness, accelerate technology transfer, and to increase public understanding of hydrogen energy systems. These challenges and the general paths forward are discussed in detail in the *National Hydrogen Energy Roadmap*.
- 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. The DOE, DOT, and other Federal agencies will play a leadership role in the development of hydrogen technologies.

> *"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

- Hydrogen and fuel cell technologies must meet market-based requirements for cost, operability, safety, maintenance, and overall performance. Given the uncertainty of overcoming all the technical hurdles, this plan assumes that the major policy (at this time) is to conduct the research, development, and validation necessary to address key technical and cost targets. The goal is "technology readiness" of hydrogen production, delivery, storage, and fuel cell technologies, to enable the automobile and energy companies to opt for commercial availability of fuel cell vehicles and hydrogen fuel infrastructure by 2020. Technology that meets consumer requirements is necessary, but not sufficient, for industry to move forward with commercialization. Portable and stationary power systems, which generally have less stringent cost targets, will likely be commercialized sooner than vehicles.

Figure ES-1. Possible Scenarios for Hydrogen Technology Development and Market Transformation




*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.*

- As shown in Figure ES-1, the Federal government will play a key role in the near term, supporting the materials and component research necessary to overcome critical path technology barriers. When the performance and durability of the technologies are validated, the government may consider becoming an early technology adopter, and could enact policies to nurture the development of an industry capable of delivering significant quantities of hydrogen to the market place. Industry's role would become increasingly dominant as market penetration increases.
- The Hydrogen Program mission is to research, develop, and validate technologies for producing, storing, delivering and using hydrogen in an efficient, clean, safe, reliable, and affordable manner. Related efforts that contribute to resolving technical barriers include DOT's fuel cell bus program, developing high-temperature fuel-flexible fuel cells for stationary applications, clean coal technologies, advanced "Gen IV" nuclear reactor technologies, carbon sequestration and carbon management technologies, renewable electric power generation, biomass and biorefinery technologies, and basic research on biological production. DOE will also continue to support development of advanced hybrid components and electric powertrain technologies for use in the next generation of hybrid vehicles and future fuel cell vehicles.
- Key program technical milestones for hydrogen technology readiness include the following:
  - Hydrogen produced from diverse, domestic resources at $2.00-$3.00 per gallon of gasoline equivalent (delivered, untaxed)[4]
  - On-board hydrogen storage systems with improved capacity to enable a driving range greater than 300 miles for most light-duty vehicles[5]
  - Polymer electrolyte-membrane (PEM) automotive fuel cells that cost $30-$45 per kilowatt and deliver 5,000 hours of service (service life of vehicle)[6]

## *Program Accomplishments*

- Built the world's first energy station that co-produces electricity and hydrogen from natural gas. This energy station demonstrated a reduction in the cost of natural gas-based hydrogen production from $5.00[7] per gallon gasoline equivalent (gge) in 2003 to $3.00[8] per gge using innovative reforming and purification technologies. The station demonstrates the synergy between the transportation and electric generation sectors of the hydrogen infrastructure. Data from laboratory research, when used in the H2A Model (see page B-2), indicate a hydrogen cost of $3.10/gge[9] based on today's natural gas reforming technology projected to high volume production.
- Reduced the high-volume cost of automotive fuel cells from $275/kW (50kW system) in 2002 to $110/kW (80kW system) in 2005[10] using innovative processes developed by national labs and fuel cell developers for depositing platinum catalyst. Additional research is needed for fuel cells to achieve the cost equivalent target of $30/kW.
- Assessed, through independent review, the status of two major technical milestones:
    - Verified the 2005 modeled cost of $110/kW for 80-kW transportation fuel cell systems (based on 500,000 units/year)[11] (the 2006 and 2010 DOE targets are $110[12] and $45[13] per kilowatt, respectively)
    - In hydrogen production, completed research on distributed natural gas reforming to achieve a hydrogen production cost of $3.00 per gallon of gasoline equivalent assuming an installation rate of 500 new forecourt stations per year (this technology will need to be validated later at full-scale)[14]
- Developed an analytical tool - the H2A model - to address the need for consistent analysis methodology and transparent reporting.[15] The model, which assesses the minimum hydrogen cost (including a return on capital investment) for a variety of hydrogen production pathways, will be used by the Program and its contractors to evaluate technologies on a common basis, to assess technology tradeoffs, and to aid systems analysis efforts. The H2A model has been beta tested using several hydrogen production pathways, including coal, natural gas, biomass, electrolysis, and forecourt receiving and dispensing. An H2A model has also been developed to assess hydrogen delivery options.
- Issued Program Research, Development, and Demonstration Plans for the Offices of Energy Efficiency and Renewable Energy; Fossil Energy; and Nuclear Energy, Science and Technology. Issued *Basic Research Needs for the Hydrogen Economy*, an Office of Science report that describes priority basic research areas for fuel cells and hydrogen production, storage, and delivery. (See Appendix E.)
- Expanded the partnership with DaimlerChrysler, Ford, and General Motors to include major energy companies (ExxonMobil Corporation, ConocoPhillips, Chevron Corporation, BP America, and Shell). Known as the FreedomCAR and Fuel Partnership, these companies will help DOE establish the technical requirements and evaluate research results for hydrogen and fuel cell technology development.

- Competitively selected over $640 million in projects (over $920 million with private cost share), subject to appropriations, to overcome critical technology barriers and to bring hydrogen and fuel cell technology from the laboratory to the showroom. Through these awards, DOE:
  - Selected 71 new hydrogen production and delivery projects ($120 million over four years) to address major technical and economic hurdles in renewable, nuclear, and coal-based hydrogen production and delivery technologies ($75 million for distributed natural gas and renewables; $43 million for coal, including 3 hydrogen utilization projects; and $2 million for nuclear-based hydrogen)[16]
  - Created a National Hydrogen Storage Project ($150 million over five years) that includes three Centers of Excellence, over 20 independent projects addressing applied research, and 17 new basic research projects.[16] The focus of these efforts, which include approximately 40 universities, 15 companies, and 10 Federal laboratories, is to develop high capacity materials and low-pressure storage technologies
  - Selected 42 new fuel cell projects, including: five projects which address critical fuel cell cost and durability issues for consumer electronics and other applications ($13 million over three years); 12 projects ($19 million over five years) for research on polymer electrolyte-type membranes with improved performance at higher temperatures and lower humidity; and 25 projects ($100 million over four years) for research in a range of fuel cell topic areas including fuel cell membranes, water transport within the stack, advanced cathode catalysts and supports, cell hardware, innovative fuel cell concepts, effects of impurities on fuel cell performance and durability, and stationary fuel cell demonstration projects to help foster international and intergovernmental partnerships[16]
  - Established a national vehicle and infrastructure "learning demonstration" project ($170 million for four teams over six years) to measure progress and help guide R&D — auto and energy company partners will identify challenges encountered when hydrogen and fuel cell technologies are operated in real-world environments.[16] This project has provided data on vehicle range, fuel cell efficiency and durability, and hydrogen quality that enables an accurate assessment of the status of the technologies in integrated operating systems
  - Selected 70 projects ($64 million over three years) in basic research to address the fundamental science underpinning hydrogen production, storage, and use[16]
  - Developed an "Introduction to Hydrogen Safety for First Responders," held pilot "Hydrogen 101" Workshops for state and local governments in six states, and launched middle school and high school curricula and teacher professional development programs ($5 million over five years)[16]
- DOE and DOT have initiated the development of first responder and code official training and education.
- Completed the Hydrogen Program Systems Analysis Plan.

- Conducted the third annual integrated Hydrogen Program Merit Review and Peer Evaluation.
- Selected members for the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) and convened the first HTAC meeting on October 2-3, 2006.
- Following a recommendation from the National Academy of Engineering, implemented a systems analysis and integration effort to integrate all Program elements (hydrogen production, delivery, and storage; fuel cells; safety, codes and standards; and education) and to monitor progress toward technology targets.
- Initiated the International Partnership for the Hydrogen Economy (IPHE), which currently includes sixteen nations and the European Commission, to foster world-wide collaboration on hydrogen technology RD&D.[17] Since the inaugural IPHE Ministerial meeting in November 2003, two IPHE Committees (Steering Committee and Implementation-Liaison Committee) have met to identify and develop collaboration mechanisms and opportunities.
- Developed the *Draft Roadmap on Manufacturing R&D for the Hydrogen Economy*.[18] The roadmap addresses challenges to manufacturing the hydrogen production, storage, and fuel cell technologies that will be required for the new hydrogen infrastructure and proposes R&D solutions to overcome such challenges. The roadmap (released by Energy Secretary Bodman on January 24, 2006) is based on the results of a July 2005 workshop and consolidates recommendations of hydrogen and fuel cell experts from industry, universities, and national laboratories. An open public comment period will gather additional feedback that will be incorporated into the final roadmap. Led by the DOE and the National Institutes of Standards and Technology, the workshop and roadmap are a result of a collaboration of the Interagency Working Group on Manufacturing R&D established though the President's National Science and Technology Council.

## Next Steps

- Assess, through independent review, the potential of cryogenic-compressed hydrogen tanks to meet DOE's 2010 targets[19]
- Transfer lessons learned from distributed reforming of natural gas to distributed reforming of renewable liquids.
- Continue to coordinate the detailed multi-year RD&D plans and priorities for hydrogen and related technology development efforts within DOE and DOT to make them consistent with this planning document, the Energy Policy Act of 2005, and the recommendations of the National Academies' studies of the Hydrogen Economy[20] and the FreedomCAR and Fuel Partnership.[21]
- Strengthen coordination by continuing to utilize the Hydrogen Program Coordination Group composed of representatives from the DOE Offices of Energy Efficiency and Renewable Energy (EE); Fossil Energy (FE); Nuclear Energy (NE); Science (SC); Policy and International Affairs (PI); and the Chief Financial Officer (CFO); and the DOT.

- Complete and publish the DOE Hydrogen Program Safety Plan and the DOE Hydrogen Program Risk Management Plan.
- Promote the sharing of safety-related information and maintain a database of safety "learnings."
- Conduct the fourth annual integrated Hydrogen Program Merit Review and Peer Evaluation.
- Reflect the importance of the following activities in the Department's out-year planning and budgeting:
  - Basic and applied research in hydrogen storage, production and delivery, and fuel cell cost and durability
  - Hydrogen delivery and analysis of infrastructure development (these activities will be closely coordinated with the 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)
  - Education activities focused on the key target audiences directly involved in near-term hydrogen technology validation
- Strengthen existing interagency coordination efforts to ensure that Federal investments in hydrogen and fuel cell technology development are leveraged to the maximum extent. The Interagency Hydrogen and Fuel Cell Technical Task Force, in accordance with the Energy Policy Act of 2005, will work toward a safe, economical, and environmentally sound hydrogen fuel infrastructure by coordinating the efforts of the Office of Science and Technology Policy; the Departments of Energy, Transportation, Defense, Commerce, and Agriculture; the Office of Management and Budget; National Science Foundation; Environmental Protection Agency; National Aeronautics and Space Administration; and other agencies as appropriate. In 2005, the task force created a website at www.hydrogen.gov to provide information on all Federal hydrogen and fuel cell activities.
- Increase awareness 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.
- Continue DOT and DOE participation in the development of Global Technical Regulations for fuel cell light duty vehicles.
- Identify opportunities to work more closely with emerging state-led initiatives to advance hydrogen infrastructure development.
- 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 and the International Energy Agency.
- Continue to implement relevant provisions of the Energy Policy Act of 2005 (see box on page xi) as appropriate.

In summary, a great deal of progress has been made in planning and carrying out the RD&D since the Hydrogen Initiative was announced in 2003. The Department of Energy expects significant results to be achieved through the President's Hydrogen Fuel Initiative in FY 2007 and beyond.

## Energy Policy Act of 2005

On July 29, 2005, Congress passed the first comprehensive energy legislation in over a decade. The Energy Policy Act of 2005 (P.L. No: 109-058)[22] was signed into law by the President on August 8, 2005 at Sandia National Laboratory in Albuquerque, New Mexico. This historic bill follows many of the principles outlined by President Bush in the National Energy Policy to strengthen our nation's electrical infrastructure, reduce our dependence on foreign oil, increase conservation, and expand the use of clean renewable energy. Title VIII of the bill focuses on hydrogen and indicates the strong support of Congress for research and development of hydrogen and fuel cell technologies. The Energy Policy Act of 2005, together with the Advanced Energy Initiative and the President's Hydrogen Fuel Initiative, shows that we have a unified commitment by our nation's leaders to reduce our dependence on foreign oil through development of more efficient energy technologies and alternative, domestically produced transportation fuels.

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# 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.

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.

### 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)

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

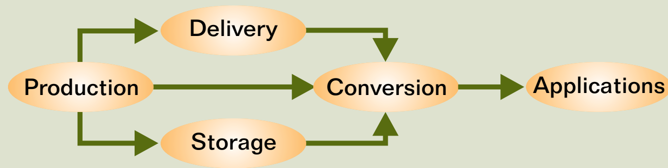
As a first step, the DOE facilitated a National Hydrogen Vision and Roadmap process and incorporated the opinions and viewpoints of a broad cross-section of stakeholders in two key documents: *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, and the *National Hydrogen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

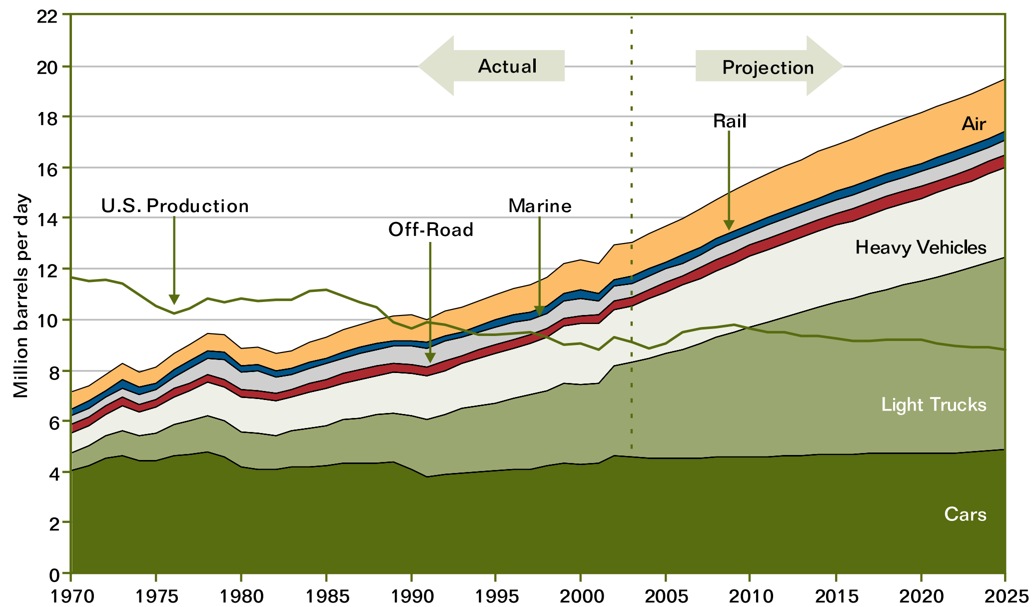
Hydrogen-powered fuel cell vehicles would not be dependent on foreign oil, because hydrogen can be produced almost entirely from diverse domestic sources of fossil, renewable and nuclear energy (see Appendix A for an example of domestic hydrogen production options and associated resource needs). Fuel 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

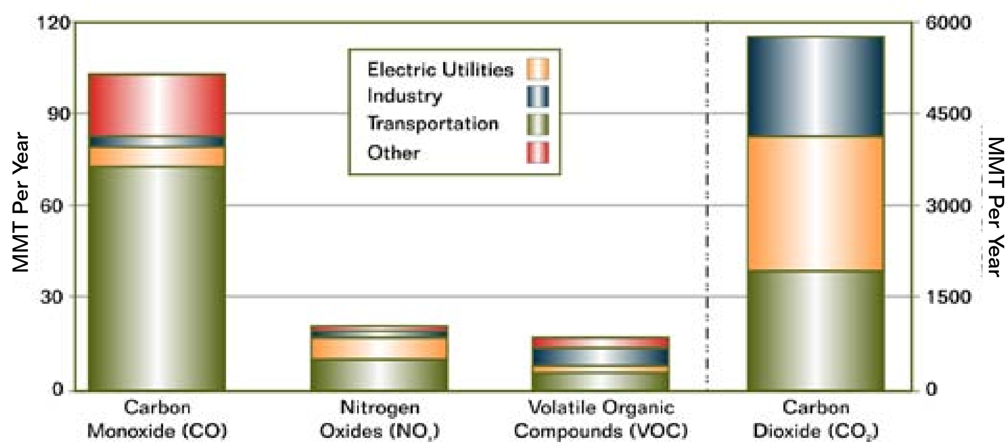



*Source:* Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 24*, (December 2004), ORNL-6973, http://cta.ornl.gov/cta/Publications/Reports/TEDB_Edition24_ORNL_6973.pdf and U.S. DOE, Energy Information Administration, *Annual Energy Outlook 2005: With Projections to 2025*, (February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

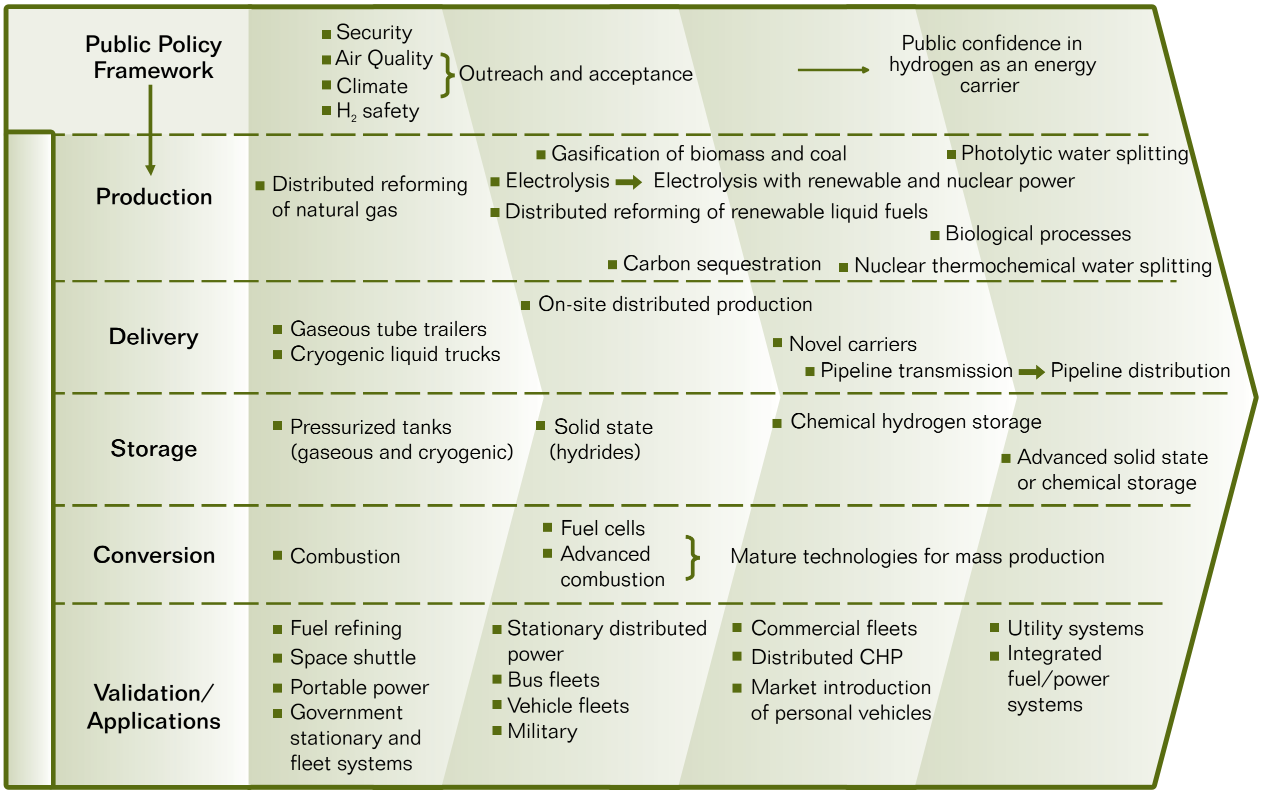
Figure 4.  Hydrogen Energy System Elements and Challenges

| 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<br>♦ Low cost and environmentally sound carbon capture and sequestration technologies<br>♦ 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<br>♦ Appropriate, uniform codes and standards<br>♦ Right-of-way for new delivery systems<br>♦ 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<br>♦ 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<br>♦ 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<br>♦ Access to accurate, objective information about hydrogen and fuel cell technologies<br>♦ 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.

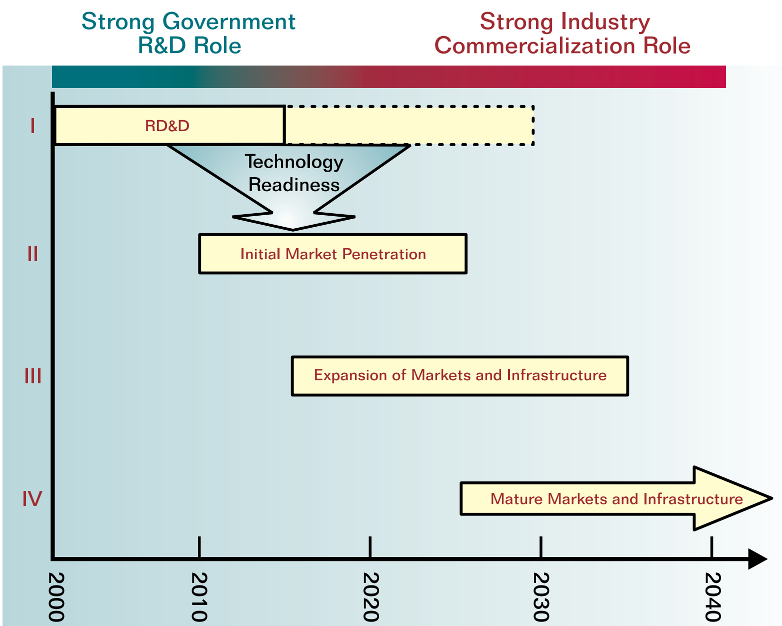
As shown in Figure 6, a hydrogen-based energy system will take significant time to develop and will require strong public and private partnerships. Currently, government and private organizations are researching, developing, and validating critical path technologies to meet customer requirements, ensure 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

# 4. Hydrogen Program

## Program Mission

The central mission of the Hydrogen Program is to research, develop, and validate hydrogen production, delivery, storage and fuel cell technologies. Development of hydrogen energy from diverse domestic 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.

## Program Strategy

The Hydrogen Program supports RD&D of hydrogen fuel cell technologies in parallel with technologies for hydrogen production and delivery infrastructure. The current focus is on addressing key technical challenges (for fuel cells and hydrogen production, delivery, and storage) and institutional barriers (such as hydrogen codes and standards to maximize safety, and training and public awareness). The Program is currently conducting basic and applied research, technology development and learning demonstrations, underlying safety research, systems analysis, and public outreach and education activities. These activities include cost-shared, public-private partnerships to address the high-risk, critical technology barriers preventing widespread use of hydrogen as an energy carrier. Public and private partners include automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, standards development organizations, other Federal agencies, state government agencies, universities, national laboratories and other national and international stakeholder organizations. The Hydrogen Program encourages the formation of collaborative partnerships to conduct RD&D and other activities that support Program goals. Figure 7 shows the types of entities that carry out activities under the Hydrogen Program and the non-Federal cost share required.

These activities address the development of hydrogen energy systems for transportation, stationary power, and portable power applications. Transportation applications include fuel cell vehicles and hydrogen refueling infrastructure. Stationary power applications include use of hydrogen for back-up emergency power and residential electric power generation. Portable power applications include consumer electronics such as cellular phones, hand-held computers, radios, and laptop computers. 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 diverse energy sources, including fossil fuel, nuclear energy, and renewable sources. Distributed reforming of natural gas and renewable liquid fuels (e.g., ethanol) is likely to be the most efficient and economical way to produce hydrogen in the near term.

As reflected in the Administration's FutureGen project, 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 carbon dioxide. With the implementation of carbon management strategies, coal could 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 mainly through basic science.

Figure 7. Types of Entities Involved in the DOE Hydrogen Program and Their Roles

| Basic Research (no cost share) | Applied Research & Technology Development (≥ 20% cost share) | Learning Demonstrations (≥ 50% cost share) |
|---|---|---|
| Universities<br>National and Federal laboratories<br>Research institutes | Equipment manufacturers and industry suppliers<br>National and Federal laboratories<br>Universities<br>Research institutes<br>Codes and standards development organizations | Automobile and energy companies<br>Industrial gas suppliers<br>Equipment manufacturers<br>Utility companies<br>State and local governments and code officials |

For information on specific organizations, projects, and contact information, go to www.hydrogen.energy.gov.

To address the need for diversified 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 Program will focus on methods to produce affordable supplies of hydrogen from water using renewable electricity (e.g., solar, wind) and nuclear sources of energy, and using direct solar conversion. In a recent report to Congress (prepared in response to Section 812(e) of the Energy Policy Act of 2005), the Program describes options, progress, and plans for developing and demonstrating solar- and wind-based hydrogen production technologies.[38] A mix of diverse energy feedstocks to produce hydrogen is needed for a secure, affordable, and environmentally safe hydrogen energy system.

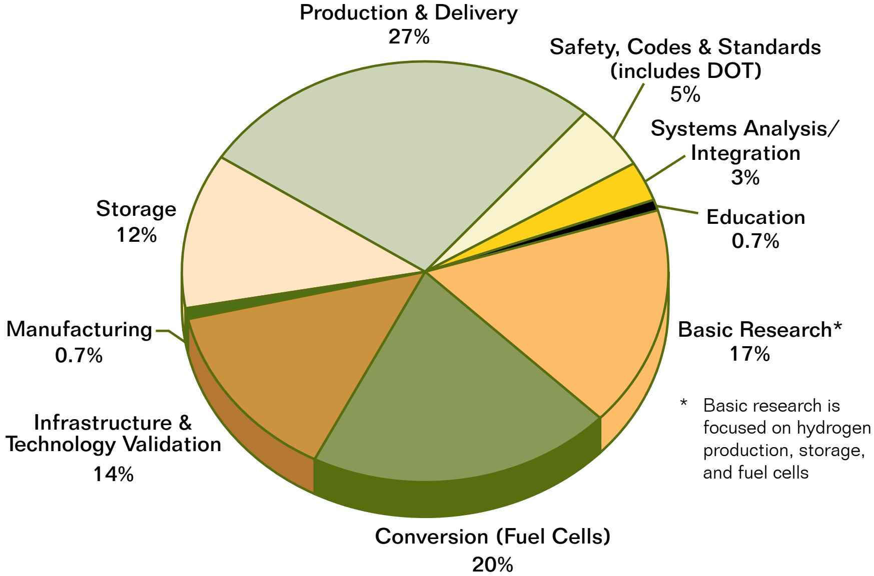
## *Program Activities and Highlights*

The $1.2 billion Hydrogen Fuel Initiative proposed by President Bush for FY 2004 through FY 2008 includes $720 million in new R&D funding over FY 2004 DOE baseline budgeting assumptions.[39] The Initiative reflects an enhanced hydrogen and fuel cell program to accelerate technology development and validation activities. The Executive Summary describes the Initiative's fiscal year (FY) 2004 and FY 2005 accomplishments. The FY 2006 appropriation includes funding for efforts in the following areas, which support the President's Hydrogen Fuel Initiative, the National Hydrogen Energy *Vision* and *Roadmap*, and the Energy Policy Act of 2005:

- Basic Research
- Production and Delivery
- Storage
- Conversion (Fuel Cells)
- Technology Validation
- Safety, Codes and Standards
- Education
- Systems Analysis and Integration

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 Program will ensure that, regardless of the pathway, common challenges are efficiently addressed. Figure 8 shows how the Initiative budget request for FY 2007 breaks out into these program areas, and the addition of a proposed new area in manufacturing R&D.

Figure 8. Hydrogen Fuel Initiative Budget Request (FY 2007)[40]




**TOTAL: $289.49 Million**

The FY 2007 budget request distributes the funding for hydrogen production and delivery research as follows:[41]

- Distributed Natural Gas ($4.2 million)
- Coal-based ($23.6 million)
- Nuclear-based ($18.7 million)
- Renewable-based ($27.6 million)
- Hydrogen Delivery ($7 million)

Related research conducted within other DOE programs will also contribute to achieving Hydrogen Program goals. These RD&D efforts are necessary to achieve a hydrogen energy pathway, but would likely be funded for other purposes even if there were no Hydrogen Program. The FY 2007 budget requests for related RD&D[42] include:

- Hybrid electric vehicle research ($109.8 million)
- Carbon sequestration and carbon management (applied R&D: $73.9 million; basic research: $5.9 million)
- Biomass and biorefinery systems (applied R&D: $150 million; basic research: $15.4 million)
- Wind energy (applied R&D: $43.8 million; basic research: $260 thousand)
- Solar energy (applied R&D: $148.4 million; basic research: $62.3 million)
- High-temperature stationary fuel cells ($63.3 million)

## Basic Research Will Target Breakthroughs in Key Areas

Recent advances in nanoscience, catalysis, modeling, simulation, and bio-inspired approaches offer exciting new research opportunities for addressing both short-term showstoppers and long-term challenges to hydrogen and fuel cell technologies. The DOE Office of Science seeks to foster fundamental understanding and 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/reports/files/NHE_rpt.pdf

- Basic research on biological hydrogen production ($50.6 million)
- DOT fuel cell bus RD&D, infrastructure development, and SAFETEA-LU activities ($28 million)

The following sections provide an overview of key ongoing and planned hydrogen activities in basic research, production, delivery, storage, conversion (fuel cells), technology validation, safety, codes and standards, education, and systems analysis and integration. Out-year planning may identify needs for additional RD&D to support and expand this portfolio of activities.

### Hydrogen Production

Lowering hydrogen production cost is a critical need. The National Academies' study[20] requested by DOE and completed in 2004 provides insight into a hydrogen feedstock strategy for the near and long term. The study has helped DOE set priorities for hydrogen production research needs. Ongoing and planned activities include the following:

- Conduct research to develop small-scale, distributed natural gas, liquid reformer, reforming, and electrolysis technologies (needed for the near term) that can operate reliably, safely, and cost-effectively in a typical fueling station using various feedstocks including natural gas, coal-derived carriers, or renewable liquids such as ethanol or other sugar derivatives. R&D activities include:
  - Improved reformer technologies using partial oxidation (or autothermal reforming) and steam reforming processes achieving higher energy efficiency and lower capital cost
  - Electrolysis technologies with reduced capital costs, enhanced system efficiency, and improved durability for distributed-scale hydrogen production from electricity and water
  - Lower-cost membranes and catalysts that can operate at higher temperatures and pressures, as well as improved system integration to lower the cost of manufacturing
- Conduct research to develop large-scale, centralized, efficient hydrogen production from coal with carbon sequestration, including:
  - Computational methods and advanced technologies to reform high hydrogen content coal-derived carriers

- Advanced water-gas shift, separation, cleanup, and process intensification technologies to produce lower-cost hydrogen
- Technologies to integrate carbon sequestration (capture and containment) with fossil-based production systems
- Multi-fueled, oxygen-blown gasification system for co-producing hydrogen and electric power

✦ Accelerate and expand research on the low-cost production of hydrogen from renewable resources, including:

- Component development and systems integration efforts that will enable electrolyzers to operate from inherently intermittent and variable-quality power derived from wind and solar sources
- Solar-driven high-temperature chemical cycle water splitting
- Photoelectrochemical systems
- Thermochemical conversion of biomass
- Photolytic and fermentative micro-organism systems

✦ Accelerate and expand research on centralized, low cost production of hydrogen using nuclear energy, including high-temperature electrolysis and sulfur-based thermochemical cycles. This activity could lead to the construction of an advanced nuclear demonstration plant with electricity and hydrogen co-production capabilities.

✦ Conduct supporting basic research for hydrogen production to enable breakthroughs in catalysis, separations, and fundamental processes including:

- Design of catalysts at the nanoscale with the main emphasis on nanoscale phenomena; innovative synthesis and screening techniques; novel characterization techniques; and theory, modeling, and simulation of catalytic pathways
- Improved understanding of light-induced dynamic processes in molecules, polymers, and semiconductor nanoparticles to support the development of low-cost solar cells and photocatalysts
- Investigation of new semiconductors, polymers, supramolecular assemblies, and catalysts (including biological or bio-inspired materials) to enable the synthesis of two- and three-dimensional chemical systems for efficient lightharvesting, charge separation, and fuel formation

## 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 from coal, including delivery, and utilization technologies where appropriate. These technologies include advanced water-gas shift reactors; and separation technologies, including membranes to separate hydrogen and/or carbon dioxide (for carbon capture and sequestration) from coal-derived synthesis gas.

## FutureGen: Coal-Fired Electricity and Hydrogen Production with Near-Zero Atmospheric Emissions

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, near-zero atmospheric emissions power plant to produce electricity and hydrogen.[43] This DOE effort, while not part of the Hydrogen Fuel Initiative, supports program goals through its objective to establish the technical and economic feasibility of producing electricity and hydrogen from coal while capturing and sequestering the carbon dioxide generated in the process. These advanced technologies offer the promise of dramatically reduced atmospheric emissions at a competitive cost with increased reliability.

### Nuclear Hydrogen Activities Will Harness Heat to Produce Hydrogen From Water

The Office of Nuclear Energy, Science & Technology (NE) will work with its partners to demonstrate the commercial-scale production of hydrogen from water using heat from a nuclear energy system. 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 thermochemical and electrolytic hydrogen production processes. NE's Nuclear Hydrogen Initiative (NHI) will conduct RD&D to develop hydrogen production technologies that can be coupled to next generation nuclear reactors. The major program elements of the NHI include the candidate production processes and high temperature interface technologies that are involved in coupling a thermochemical or high-temperature electrolysis plant to an advanced high-temperature reactor.

### The Solid State Energy Conversion Alliance (SECA) Will Fast-Track Commercialization of Solid Oxide Fuel Cells and Develop Fuel Cell Technology for FutureGen

While not part of the Hydrogen Fuel Initiative, SECA is a parallel effort to reduce cost and achieve technology breakthroughs in solid oxide fuel cells (SOFCs). The materials and engineering developments achieved through SECA may also have applications in other fuel cell technologies. The goal of this joint government-industry effort is to develop 3-10kW SOFCs by 2010 that can be mass-produced in modular form, and to scale-up the technology to serve as building blocks for FutureGen type plants. SECA fuel cells will be used for a broad array of applications, including auxiliary power and combined heat and power. A ten-fold cost reduction over existing technology is required to reach the goal of producing SOFCs at $400/kW. Key milestones include:

By 2010, develop modular and scalable 3-10kW distributed generation fuel cell designs at $400/kW and 40-60% LHV efficiency.

By 2015, demonstrate MW-class coal and carbon sequestration ready fuel cell or fuel cell/turbine hybrid systems at $400/kW, 50% HHV efficiency (75% with natural gas) and 90% $CO_2$ capture.

By 2020, demonstrate 100 MW–class fuel cell/turbine hybrid system fueled by coal gasification.

More information on the SECA Program can be found at http://www.seca.doe.gov/.

   - Improved understanding of the pathways by which hydrogen is made and processed in living organisms to enable breakthroughs in feasible photobiological and biological reactor technologies
   - Investigation of membrane materials for separation, purification, and ion transport including integrated nanoscale architectures; fuel cell membranes; and theory, modeling, and simulation of separation processes and mechanisms

## Hydrogen Delivery

Delivery technologies and economics will heavily influence the level of infrastructure investment and safety assurance required. New concepts will be needed to reduce delivery costs from the point of hydrogen production to the point of use at refueling stations and distributed power facilities. Systems analysis of delivery alternatives will show the lifecycle cost advantages and disadvantages of the alternative approaches for transporting hydrogen over long distances and will identify areas in which R&D could provide the greatest cost reductions and the greatest value. Ongoing and planned R&D activities include the following:

- Conduct research to lower the cost of the hydrogen delivery infrastructure, including the development of:
   - More reliable lower-cost compression technology
   - Lower cost gaseous hydrogen tank technology and systems for stationary storage and tube trailers
   - More energy efficient and lower cost liquefaction technology
   - Improved pipeline materials to resolve hydrogen embrittlement concerns and to reduce capital costs
   - New liquid or solid hydrogen carriers (e.g., metal or chemical hydrides, carbon-based materials, etc.) that can increase the energy density of hydrogen transport
- In coordination with the DOT, develop technologies (e.g., seals, valves, sensors and controls) to ensure the safety of the hydrogen delivery system

## The FreedomCAR and Fuel Partnership Seeks a Clean and Sustainable Transportation Energy Future

The FreedomCAR and Fuel Partnership is a government-industry partnership including the U.S. DOE, the U.S. Council for Automotive Research (members include Ford Motor Company, General Motors Corporation, and DaimlerChrysler Corporation), and five major energy companies (BP America, Chevron Corporation, ConocoPhillips, ExxonMobil Corporation, and Shell). The collaboration was formed to examine the pre-competitive, high-risk research needed to develop the component and infrastructure technologies necessary to enable a full range of affordable cars and light trucks, including the fueling infrastructure. These new technologies will reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice. The C-A-R in FreedomCAR stands for Cooperative Automotive Research.

> *The goals of this program are extremely challenging and success is uncertain, but it could have an enormous beneficial impact on energy security and the U.S. economy. Although it is still too early to speculate whether the program will achieve its long-term vision, it is making significant headway.*
>
> — Craig Marks, Chair of the NRC Committee on Review of the FreedomCAR and Fuel Research Program, NAS Press Release, August 2, 2005[44]

The long-term vision of the Partnership is a clean and sustainable transportation energy future. A major thrust of the Partnership is to identify and address the technologies necessary to enable high volume production of affordable hydrogen fuel cell vehicles and fuels, and the national infrastructure necessary to support them. Additionally, the Partnership addresses technology needs to enable mass penetration of hybrid electric and advanced combustion vehicles that also offer the potential to significantly reduce the nation's dependence upon imported oil. The Partnership Plan identifies technology-specific goals for 2010 and 2015 to promote R&D innovation (the plan can be downloaded from www.eere.energy.gov/vehiclesandfuels/). In addition to the hydrogen and fuel cell technology goals described in this Posture Plan, the key FreedomCAR partnership goals for advanced hybrid vehicle technologies include:

- Electric propulsion system with a 15-year life capable of delivering at least 55 kW for 18 seconds, and 30 kW continuously at a system cost of $125/kW peak
- Internal combustion engine powertrain systems costing $30/kW, having a peak brake engine efficiency of 45%, and meeting or exceeding emission standards
- Electric drivetrain energy storage with a 15-year life at 300 Wh 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

The detailed R&D plan for advanced vehicle technologies can be found at www.eere.energy.gov/vehiclesandfuels/resources/fcvt_mypp.shtml.

*DaimlerChrysler F-Cell*

*Ford Focus*

*GM Sequel*

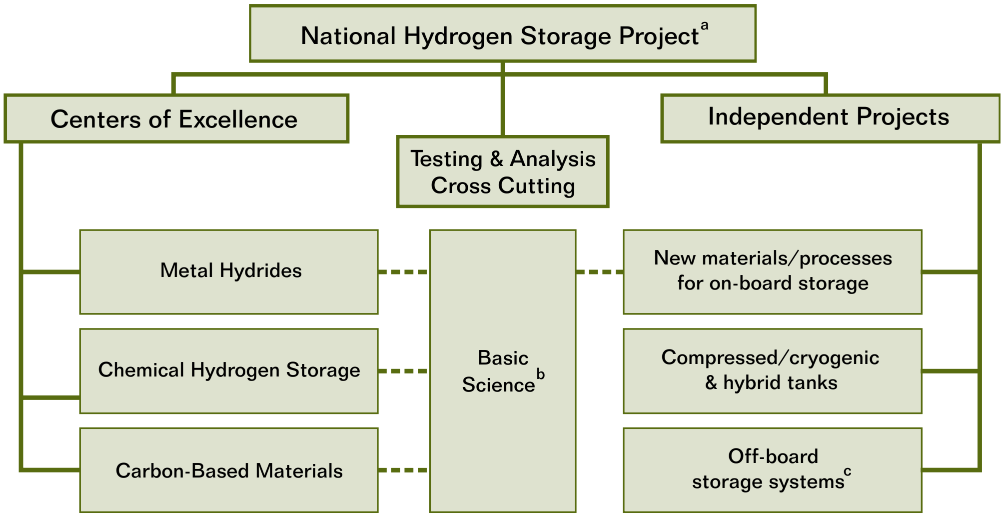
- Supporting basic research needs include:
  - Improved understanding of how hydrogen reacts and interacts with the surface, interface, grain boundaries, and bulk defects of particular materials to clarify the mechanisms of hydrogen embrittlement and help guide proper selection of existing materials or discovery/design of suitable new materials (e.g., nanostructured composites, advanced polymers)
  - Design/development of novel new materials for off-board (bulk) hydrogen storage or as hydrogen carriers

### Hydrogen Storage

Lower-cost, lighter-weight, and higher-density hydrogen storage is one of the key technologies needed for the introduction of hydrogen-based systems. Advanced storage materials that show promise include complex metal hydrides, chemical hydrides, carbon structures, and metal organic frameworks. Understanding how to produce and contain these advanced materials will be required as well as how to fill and discharge hydrogen, manage pressure and thermal properties, and integrate the materials into practical systems for stationary and mobile applications. The DOE's "Grand Challenge" solicitation for Hydrogen Storage formed the basis for the National Hydrogen Storage Project (depicted in Figure 9), which involves approximately 40 universities, 15 companies, and 10 Federal laboratories in conducting R&D to address these challenges.[12] Ongoing and planned hydrogen storage R&D includes the following activities:

- Complete research, including materials work, to validate high-pressure and cryogenic tanks as near-term approaches
- Develop and evaluate innovative storage approaches including reversible storage materials, such as carbon nanotubes and metal hydrides, regeneration issues related to chemical hydrides, and other novel materials and concepts
- Downselect pure, undoped, single-walled carbon nanotube technology based on material capacity of six wt % hydrogen[15]
- Conduct collaborative research on complex metal hydrides, chemical hydrides, and carbon-based materials at the Centers of Excellence through the National Hydrogen Storage Project
- Conduct basic research, with an emphasis on understanding the chemical and physical processes governing materials-hydrogen interactions to enable the design and discovery of new, higher-capacity hydrogen storage materials, including:
  - Investigation of new properties and capabilities offered by nanostructures to further enhance storage capacity and to improve uptake/release kinetics
  - Design of two- and three-dimensional nanoarchitectures to improve the capabilities of today's metal and complex hydrides
  - Theory, modeling, and simulation approaches
  - Novel analytical and characterization tools

Figure 9. Organization of the National Hydrogen Storage Project




a Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies

b Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences

c Coordinated with Delivery Program element

## Conversion (Fuel Cells)

Reducing fuel cell cost (by a factor of approximately 4)[45] and improving durability and reliability will be required to ensure the commercial viability of fuel cells in both mobile and stationary applications. Fuel cell research will continue on high-efficiency polymer electrolyte membranes (PEMs) and other stack components and systems to meet cost, durability, power density, heat utilization, cycling, load-following, operation and start-up in cold weather, and other key performance targets. In 2004, DOE conducted a go/no-go review of on-board fuel processing activities. The review resulted in a no-go decision, concluding that on-board fuel processing would not improve sufficiently from its current status to compete effectively with gasoline hybrid vehicles or to support a hydrogen infrastructure. Projects that focus on on-board fuel processing have therefore been terminated or redirected to support development of fuel processors for stationary applications or development of catalysts suitable for a variety of fuel processing applications (e.g., auxiliary power units). Ongoing and planned fuel cell R&D includes the following activities:

- Focus on overcoming critical technical hurdles at the component level to improve overall polymer electrolyte membrane fuel cell performance and durability while lowering costs, including:
    - Proton-conducting membranes that operate at 120°C[46] (maximum) for transportation applications and greater than 120°C[47] for stationary applications
    - Membranes that can operate at low relative humidity
    - Cathodes with decreased precious metal loading
    - Non-precious metal cathode catalysts
    - Bipolar plate materials and coatings with improved corrosion resistance

- Continue the development of auxiliary power unit systems for heavy vehicle application and the feasibility assessment of fuel cells for portable power applications
- Evaluate the impact of hydrogen quality (i.e., tolerance to impurities) on fuel cell performance and durability
- Independently review the status of progress toward critical targets, such as cost
- Conduct research to address technology shortfalls associated with cold-weather start-up and operations
- Conduct basic research to:
  - Better characterize the mechanisms of ionic (including protonic) transport in fuel cell materials (including dependence on relative humidity, temperature, acidity, etc.)
  - Improve understanding of the relationship between precious metal catalytic behavior (catalytic activity, selectivity, deactivation, etc.) and catalyst composition, crystal structure, and morphology to guide design of new, non-precious metal catalysts
  - Improve understanding and ability to control the electrochemical processes at the electrodes and membrane electrolyte interfaces

### Manufacturing

R&D is needed to reduce manufacturing cost of evolving hydrogen technologies and develop a domestic supplier base. In support of the President's Manufacturing Initiative and Hydrogen Fuel Initiative, the manufacturing R&D effort will enable the mass production of both supply and end-use technologies – in parallel with technology development – and will foster a strong domestic supplier capability. Activities will address the challenges of moving today's laboratory produced technologies to high-volume, pre-commercial manufacturing thereby driving down the cost of hydrogen and fuel cell systems. Research will be conducted in coordination with the Department of Commerce and the White House Office of Science and Technology Policy's Interagency Working Group on Manufacturing R&D. A research and development technology roadmap has been developed with industry to identify critical technology development needs for high volume manufacturing of fuel cell and hydrogen systems. Planned activities include:

- Conduct research to design innovative and cost-effective manufacturing processes and technologies for PEM fuel cells, potentially including:
  - Investigation of an array of fabrication and process techniques amenable to high volume production of fuel cells, hydrogen production, delivery, and storage components and systems
  - Research on manufacturing of technologies critical to near-term technology deployment, such as 1) membrane electrode assemblies and bipolar plates for fuel cells, 2) distributed reforming and electrolysis systems and components for producing hydrogen, and 3) vessels, valves, and regulators for hydrogen storage and dispensing
- Support technical, market, economic, and other analyses to address manufacturability and cost reduction in critical technology areas, i.e., hydrogen production and delivery, hydrogen storage, and fuel cells

Figure 10. National Hydrogen Learning Demonstration Project

DTE/BP Power Park, Southfield, MI


Shell hydrogen station and GM fuel cell vehicle, Washington, D.C.

BP hydrogen station, Los Angeles, CA


DaimlerChrysler fuel cell vehicle

Chevron hydrogen station and Hyundai fuel cell vehicle, Chino, CA

Ford fuel cell vehicle

The National Hydrogen Learning Demonstration includes four industry teams that are working towards meeting the 2009 targets listed below.

| Performance Measure | 2009* | 2015** |
|---|---|---|
| Fuel Cell Stack Durability | 2000 hours | 5000 hours |
| Vehicle Range | 250+ miles | 300+ miles |
| Hydrogen Cost at Station | $3.00/gge | $2.00 - $3.00/gge |

* To verify progress toward 2015 targets ** Subsequent projects to validate 2015 target

## Technology Validation

Efforts are needed to validate hydrogen energy systems (including fuel cells, engines, and turbines) in mobile and stationary applications. "Learning demonstrations" provide technical data on operation in a real world environment to measure progress and to help guide the research program as well as financial data for determining market and investment risks. The National Hydrogen Learning Demonstration Project (see Figure 10) will support a statistically significant number of hydrogen vehicle and refueling station demonstrations in several locations to:

- Validate technology status and develop data to guide R&D addressing:
    - Hydrogen fueling station safety, operations, and reliability; vehicle fueling interface; and hydrogen production efficiency and cost
    - Vehicle performance and reliability under real operating and climate conditions
- Validate safety and performance data from power park systems to coproduce hydrogen and electricity for vehicles and grid, respectively

Demonstration projects will also be conducted through DOT and the Safe, Accountable, Flexible, Transportation Equity Act: A Legacy for Users or SAFETEA-LU (see box on page 24).

## Safety, Codes and Standards

Commercialization of hydrogen technologies cannot proceed unless effective domestic and international codes and standards are in place. DOE and DOT, in collaboration with Environmental Protection Agency, National Institute of Standards and Technology, Department of Defense, National Aeronautics and Space Administration, and other agencies, can play a role in fostering

### Department of Transportation Demonstrations Focus on Fuel Cell Buses and Related Infrastructure

The Department of Transportation (DOT) established the Hydrogen and Fuel Cell Bus Initiative to help pave the way for successful commercialization of fuel cells in other transportation applications. These activities do not fall within the scope of the Hydrogen Fuel Initiative, but are closely related as transit buses will likely be one of the early markets for hydrogen and fuel cell technologies based on the fundamental characteristics of transit bus operations. The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)[48] supports DOT's fuel cell bus activities. SAFETEA-LU (P.L. 109-59) was enacted on August 10, 2005, and authorizes programs through FY 2009 for highways, highway safety, transit, and other transportation purposes. Section 3045 of the law directs the Secretary of Transportation to establish a national fuel cell bus program to aid development of commercially viable fuel cell bus technology and related infrastructure.

codes and standards development. Ongoing and planned efforts include the following:

- Conduct top-down safety analysis of hydrogen-related processes and equipment for transportation and stationary applications and begin identifying design requirements
- Assist national and international code developers in developing and disseminating new building codes and equipment standards, including:
  - 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
  - Product safety and performance standards and design requirements for vehicles, fuel cells, storage tanks, and other products and equipment that handle hydrogen or hydrogen-carrier fuels
- Develop best safety practices, including publication of a Best Practices Manual in 2007
- Document and disseminate safety "learning" on a national basis

## Education and Outreach

The President's National Energy Policy and the Energy Policy Act of 2005 recommend education activities to communicate the benefits of alternative energy, including hydrogen. Effective education is critical to enabling the successful implementation of near-term hydrogen demonstration projects and early market fuel cell installations, as well as the longer-term market adoption and acceptance that is required to realize the benefits of hydrogen and fuel cell technologies. Key audiences include state and local governments (including safety, code, and zoning officials), educators, professional and trade organizations, real estate developers and building owners and operators, public and private fleet operators, and the general public. Ongoing and planned education efforts include the following:

- Develop educational materials for state and local government officials and potential end users to help ensure an understanding of state-of-the-art hydrogen technologies, hydrogen safety, opportunities, and timing for facilitating the introduction of fuel cell vehicles and supporting hydrogen infrastructure
- Develop and implement training modules for safety and code officials

- Conduct activities to educate the public and key target audiences in communities where new hydrogen fueling stations will be implemented as part of technology validation
- Facilitate the expansion of hydrogen and fuel cell programs and learning modules at educational institutions, including:
  - Trade schools, colleges, and universities, for use in training a workforce of engineers and technicians and to engage students in a variety of disciplines in resolving the challenges to hydrogen technologies and infrastructure
  - Elementary and secondary schools, to engage younger students in the study of science and technology and to ensure an informed first-generation of hydrogen technology users

### Systems Analysis

Systems analysis, aided by various modeling tools, will be used in the program management process to establish goals, evaluate tradeoffs, set priorities, and make technology down-selects and go/no-go decisions. Analysis will be required to assess the challenges, evaluate the contribution and interaction of the individual components, and support R&D efforts to resolve the technical barriers. The conversion from carbon-based to carbon-neutral energy technologies will require well-to-wheels analysis of cost, greenhouse gas emissions, energy efficiency, distribution, and analysis of nontechnical issues such as policy requirements and consumer preference. Analysis and modeling of components, pathways, and development scenarios will be a continual process that is directly linked to the Technology Validation activity. Ongoing and planned activities include the following:

- Conduct well-to-wheels analysis of production, delivery, and storage pathways to enable informed tradeoff decisions
- Conduct analysis to predict vehicle and component characteristics to evaluate technology options and tradeoffs
- Conduct analysis to examine infrastructure development, resource availability, and cost goals
- Develop a comprehensive macro-system model to analyze options and tradeoffs and better understand infrastructure constraints and barriers to the use of hydrogen as an energy carrier
- Validate the models and evaluations using the results of the learning demonstration efforts
- Compare the analysis of hydrogen fuel cell pathways to other technologies and fuels such as hybrid vehicles (gasoline, plug-in hybrid), all-electric vehicles, or vehicles that run on alternative fuels such as ethanol

### Systems Integration

The breadth and complexity of the overall RD&D effort, as well as the interaction of program elements, requires an integrated Program approach to reduce risk and maximize the potential for technology readiness. Systems Integration will ensure all requirements are being addressed; track and measure the progress of projects; conduct independent analysis to aid the multiple programmatic decisions that need to be made over the course of the program;

support a performance-based management approach; and identify and quantify programmatic and technical risks to ensure the program is proactive in response to issues and challenges. Ongoing and planned activities include:

- Develop and maintain an Integrated Baseline for the DOE Hydrogen Program that links technology requirements, current status, costs, and schedule
- Provide independent analysis supporting key program milestones and decisions, including an effort to evaluate the potential of cryogenic compressed hydrogen tanks to meet DOE's 2010 storage targets[19]
- Verify performance of RD&D efforts and progress toward meeting the program's technical targets
- Provide hydrogen infrastructure modeling and simulation capabilities in support of systems analysis
- Facilitate the implementation of risk management and configuration management/change control processes to enhance Program effectiveness

### Hydrogen Cost Goal

In 2005, the DOE developed a new hydrogen cost goal.[4] The hydrogen cost goal, which is independent of the production pathway, was adjusted from $1.50 to $2.00-$3.00 per gallon of gasoline equivalent (gge) based on the Energy Information Administration's forecast of gasoline cost in 2015, and the relative fuel economy of hydrogen fuel cell vehicles to advanced vehicle technology in 2015. The methodology used ensures that consumers' operating cost ($/mile) in a hydrogen fuel cell vehicle will be equal to or less than the competitive gasoline vehicle in 2015.

## *Program Milestones*

The milestone chart shown in Figure 11 (see pages 28-29) presents the key activities of the Hydrogen Program through completion of critical path technology development. The Program is projected to continue beyond this point to support basic science and RD&D on advanced technologies and longer-term, centralized hydrogen production alternatives that are carbon-neutral. The milestones are organized according to the National Hydrogen Energy Roadmap's key elements.

Milestones for each of the timelines specify a delivery date for the given technology development, improvement or validation effort. Some milestones have slipped due to shortfalls in appropriations or changes in program planning. The values given are compiled mainly from the EE, FE, and NE RD&D Plans, but include other sources such as DOE analysis, the FreedomCAR and Fuel Partnership Plan, the National Hydrogen Energy Roadmap, DOT, and ongoing Federal laboratory research. As technologies evolve and economic and systems analyses progress, these targets will be refined.

The milestones listed in Figure 11 describe DOE hydrogen RD&D activities at a high level of aggregation and do 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. (See office-level multi-year plans, listed in Appendix E, for a more detailed description of milestones and activities.) Some production technologies, such as photoelectrochemical, will require development beyond this time frame to be cost-competitive with other hydrogen production methods.

For each milestone, 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 (i.e., high-volume) production.

As described in the text box, a new hydrogen cost target and methodology was recently developed by DOE. The new cost target of $2.00-$3.00 per gallon of gasoline equivalent (delivered, untaxed, 2005$) is independent of the pathway or feedstock cost used to produce and deliver the hydrogen, and provides a range reflecting variability in future fuel efficiency improvement factors. The cost target will be used to guide the Department's hydrogen and fuel cell research and development activities.

*The effective management of the Department of Energy hydrogen program will be far more challenging than any activity previously under-taken on the civilian energy side of the DOE.*

— The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Academy of Sciences, February 2004

As technical milestones are achieved, market or end-user incentives may be needed to overcome additional 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 widespread acceptance of the technology. Detailed analysis of life-cycle costs and benefits and environmental impacts will continue to inform decisions regarding future hydrogen research.

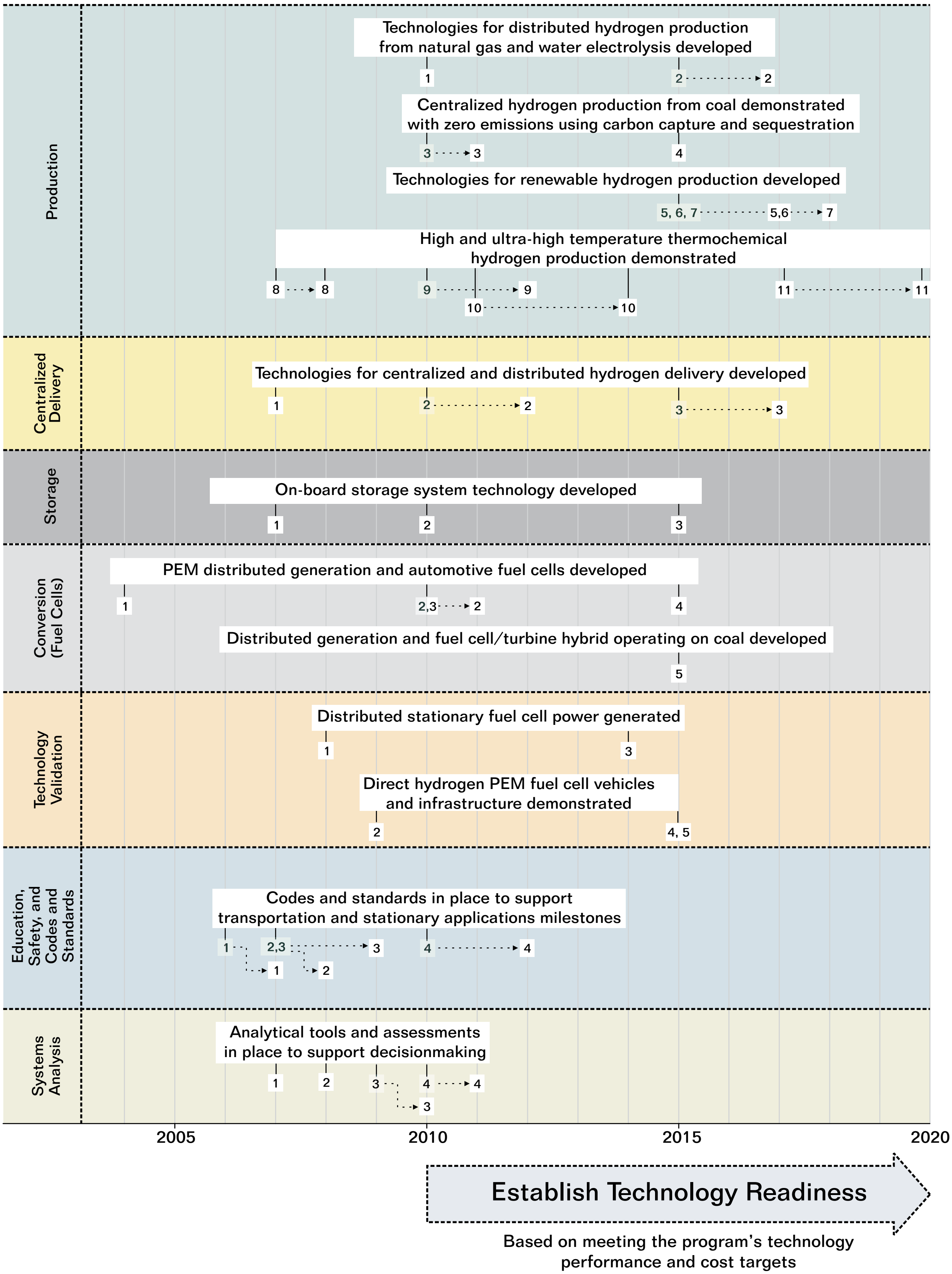
## Integrated Program Management and Coordination

The Hydrogen Program currently includes participation from the DOE Offices of Energy Efficiency and Renewable Energy (EE); Fossil Energy (FE); Nuclear Energy, Science and Technology (NE); and Science (SC); and the DOT. Each office manages activities addressing hydrogen technologies that are consistent with their respective missions and objectives, in accordance with the guiding documents shown in Figure 12. 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 hydrogen is the ability to use a diverse set of energy resources for supply. The program's research activities will provide the U.S. 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., transportation systems, stationary power generation stations, and portable power devices), 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 has been developed to provide more detail on how DOE hydrogen activities will be integrated and managed within the Department. The Interagency Hydrogen and Fuel Cell Technical Task Force meets regularly to share information and coordinate Federal government activities. The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) has been chartered in accordance with the Energy Policy Act of 2005 to advise the Secretary of Energy on the Hydrogen Program. External evaluation is

Figure 11.  Technology Development Timeline:  Milestones and Decision Points[a]



## Figure 11 (cont'd). Legend for Technology Development Timeline[a]

### Production Milestones[b]

**Distributed Natural Gas and Electrolysis**

1. 2010: Develop technology to produce hydrogen from natural gas at a refueling station that projects to a cost of $2.50/gge for hydrogen. [At the pump, untaxed, at 5,000 psig]
2. 2015 → 2017: Develop technology to produce hydrogen utilizing distributed electrolysis that projects to a cost of <$3.00/gge. [At the pump, untaxed, at 10,000 psig]

**Central Coal**[c, d]

3. 2010 → 2011: Develop pre-engineering membrane separation modules and reactors for hydrogen production that meet membrane cost target of $150-200/ft$^2$
4. 2015: Demonstrate a near-zero atmospheric 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 (ultimate target: $1.80/gge delivered)

**Renewable Resources**[e]

5. 2015 → 2017: Develop technology to produce hydrogen through distributed reforming of renewable liquid fuels at a refueling station that projects to a cost of <$3.00/gge for hydrogen [At the pump, untaxed, at 10,000 psig]
6. 2015 → 2017: Develop technology for central hydrogen production integrating wind electricity production and electrolysis that projects to a cost of <$2.00/gge at the plant gate (<$3.00/gge delivered)
7. 2015 → 2018: Demonstrate laboratory-scale photobiological water splitting system to produce hydrogen at an energy efficiency of 5% (solar-to-hydrogen). Demonstrate laboratory-scale photoelectrochemical water splitting system to produce hydrogen at an energy efficiency of 10% (solar-to-hydrogen)

**High-Temperature Thermochemical**[f]

8. 2007 → 2008: Operate laboratory-scale thermochemical and electrolytic processes to determine the feasibility of coupling them with a nuclear reactor
9. 2010 → 2012: Laboratory-scale demonstration of solar-driven high-temperature thermochemical hydrogen production that projects to a cost $6.00/gge (ultimate target: $7.00/gge delivered)
10. 2011 → 2014: Pilot-scale demonstration of thermochemical hydrogen production system for use with nuclear reactors that projects to a cost of $2.50/gge (ultimate target: $3.50/gge delivered)
11. 2017 → 2020: Engineering-scale demonstration of thermochemical hydrogen production system for use with nuclear reactors that projects to a cost less than $2.00/gge ($3.00/gge delivered)

### Storage Milestones

1. 2007: 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 1,500 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, 2,700 watt hours/ liter, and $2.00/kWh

### Validation Milestones

1. 2008: Validate stationary fuel cell system that co-produces hydrogen and electricity at 20,000 hours durability with 40% efficiency at a cost of $1500/kW or less
2. 2009: Validate polymer electrolyte membrane fuel cell vehicles at multiple sites, achieving 2,000 hours durability, a 250-mile range, and $3.00/gge of hydrogen
3. 2014: 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. 2015: Validate PEM fuel cells on operational vehicles in different climatic conditions that can be produced for $45/kW when produced in quantities of 500,000
5. 2015: Validate polymer electrolyte membrane fuel cell vehicles achieving 5,000 hours durability (service life of vehicle) and a 300-mile range

### Conversion Milestones[e]

1. 2004: Decision to discontinue on-board fuel processing R&D based on inability to achieve 78% efficiency and <0.5 minute start time
2. 2010 → 2011: Distributed stationary generation natural gas/propane 5-250 kW fuel cell go/no-go decision based on ability to achieve: 40% electrical efficiency, 40,000 hours durability (equivalent to service life between major overhauls), at a cost of less than $400-$750/kW (depending on application)
3. 2010: Develop direct hydrogen polymer electrolyte membrane automotive fuel cell operating at 60% peak efficiency, 220 W/L density, 325 W/kg 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 HHV efficiency of 50% with carbon sequestration

### Education, Safety, and Codes and Standards Milestones[e]

1. 2006 → 2007: Facilitate publishing domestic and international hydrogen quality standards and publish initial set of basic safety training materials
2. 2007 → 2008: Publish initial Best Practices manual for hydrogen safety
3. 2007 → 2009: Education program for safety and code officials in place
4. 2010 → 2012: Initial set of technical codes and standards in place to support demonstrations, commercialization decisions and regulatory standards

### Centralized Delivery Milestones[e]

1. 2007: Define the criteria for a cost-effective hydrogen fuel delivery infrastructure for supporting the introduction and long-term use of hydrogen for transportation and stationary power
2. 2010 → 2012: 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 <$1.70/gge of hydrogen
3. 2015 → 2017: 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

### Systems Analysis Milestones[e]

1. 2007: Complete technoeconomic analysis of current production technologies
2. 2008: Develop a macro-system model of the hydrogen fuel infrastructure to support the transportation system
3. 2009 → 2010: Complete assessment of hydrogen quality requirements for production, delivery, storage and fuel cell pathway
4. 2010 → 2011: Develop electricity infrastructure module for the macro-system model

[a] *Achieving the milestones is dependent on requesting and receiving funding at the Hydrogen Program planning levels for each office.*

[b] *The hydrogen cost milestones are not yet normalized across the Hydrogen Program. The Program is in the process of normalizing the criteria used to determine the Hydrogen Program cost goals using the recently-developed "H2A" modeling tool.*

[c] *The assumed feedstock cost for coal is $29.00/short ton.*

[d] *Milestone delay due to changes in Fossil Energy program planning.*

[e] *Milestone delays are due to shortfalls in appropriations.*

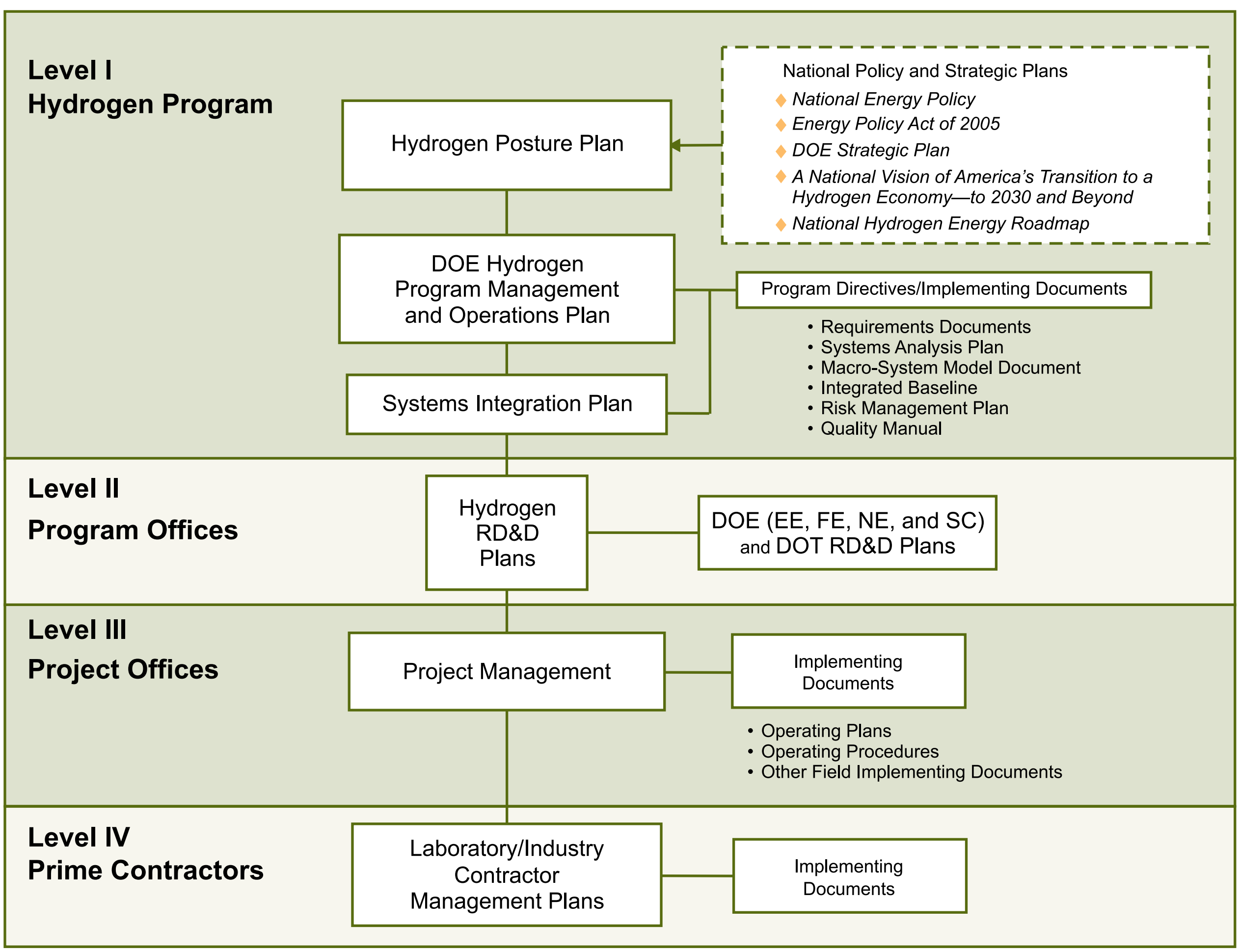
[f] *Milestone delays are due to changes in the DOE budget planning profile.*

also provided through a quadrennial review of the Program by the National Academy of Sciences in accordance with the Energy Policy Act of 2005.

The DOE Hydrogen Program Manager, responsible for coordinating all the Department's hydrogen activities, is located within the Office of Energy Efficiency and Renewable Energy, the lead organization for the President's Hydrogen Fuel Initiative. An internal Hydrogen Program Coordination Group has been established (comprised of representatives of DOT and the DOE Offices of EE, FE, NE, SC, PI, and CFO) to:

- Evaluate the progress of the Department's hydrogen and related activities with regard to milestones and performance goals
- Strengthen information exchange on programmatic and technical developments
- Ensure that the various program activities (e.g., budgeting, execution, reporting, and evaluation) remain well-coordinated
- Provide suggestions for management improvements and enhanced technical performance

Figure 12. Program Document Hierarchy



- Collaborate on systems analysis to understand the economic, energy, and environmental impacts of alternative technology pathways

International cooperation and collaboration will also be important to efficiently achieve national hydrogen and fuel cell technology goals.  The DOE has led the creation of the International Partnership for the Hydrogen Economy, which facilitates global cooperative R&D efforts, common codes and standards, and sharing of information necessary to develop a hydrogen fuel infrastructure.

# 5. Next Steps

- Assess, through independent review, the potential of cryogenic-compressed hydrogen tanks to meet DOE's 2010 targets[15]
- Continue to coordinate the detailed multi-year RD&D plans and priorities for hydrogen and related technology development efforts within DOE and DOT to make them consistent with this planning document, the Energy Policy Act of 2005, and the recommendations of the National Academies' studies of the Hydrogen Economy[20] and the FreedomCAR and Fuel Partnership.[21]
- Strengthen coordination by continuing to utilize the Hydrogen Program Coordination Group composed of representatives from the DOE Offices of Energy Efficiency and Renewable Energy (EE); Fossil Energy (FE); Nuclear Energy (NE); Science (SC); Policy and International Affairs (PI); and the Chief Financial Officer (CFO); and the DOT.
- Complete and publish the DOE Hydrogen Program Safety Plan and the DOE Hydrogen Program Risk Management Plan.
- Promote the sharing of safety-related information and maintain a database of safety "learnings."
- Conduct the fourth annual integrated Hydrogen Program Merit Review and Peer Evaluation.
- Reflect the importance of the following activities in the Department's out-year planning and budgeting:
  - Basic and applied research in hydrogen storage, production and delivery, and fuel cell cost and durability
  - Hydrogen delivery and analysis of infrastructure development (these activities will be closely coordinated with the 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)
  - Education activities focused on the key target audiences directly involved in near-term hydrogen technology validation
- Strengthen existing interagency coordination efforts to ensure that Federal investments in hydrogen and fuel cell technology development are leveraged to the maximum extent. The Interagency Hydrogen and Fuel Cell Technical Task Force, in accordance with the Energy Policy Act of 2005, will work toward a safe, economical, and environmentally sound hydrogen fuel infrastructure by coordinating the efforts of the Office of Science and Technology Policy; the Departments of Energy, Transportation, Defense, Commerce, and Agriculture; the Office of Management and Budget; National Science Foundation; Environmental Protection Agency; National Aeronautics and Space Administration; and other agencies as appropriate. In 2005, the task force created a website at www.hydrogen.gov to provide information on all Federal hydrogen and fuel cell activities.

- Increase awareness 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.
- Continue DOT and DOE participation in the development of Global Technical Regulations for fuel cell light duty vehicles.
- Identify opportunities to work more closely with emerging state-led initiatives to advance hydrogen infrastructure development.
- 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 and the International Energy Agency.
- Continue to implement relevant provisions of the Energy Policy Act of 2005 (see box on page xi) as appropriate.

In summary, a great deal of progress has been made since 2003 in planning and carrying out the research, development, and demonstrations. The Department of Energy expects significant results to be achieved through the President's Hydrogen Fuel Initiative in FY 2006 and beyond.

# Notes

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2 U.S. Department of Energy, *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond* (February 2002), retrieved January 20, 2006 from http://www.hydrogen.energy.gov/pdfs/vision_doc.pdf.

3 U.S. Department of Energy, *National Hydrogen Energy Roadmap* (November 2002), retrieved January 20, 2006 from http://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf.

4 U.S. Department of Energy (Hydrogen Program), "Record 5013: Hydrogen Cost Goal," http://www.hydrogen.energy.gov/program_records.html.

5 FreedomCAR and Fuel Partnership, *Hydrogen Storage Technologies Roadmap* (November 2005), retrieved October 6, 2006, from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/hydrogen_storage_roadmap.pdf. The 300 mile driving range for hydrogen powered vehicles was set to be comparable to the 370 mile driving range of a weighted average corporate vehicle, the presumed preference of the average U.S. consumer, p. 7.

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7 U.S. Department of Energy (Hydrogen Program), "Record 5030: Hydrogen Baseline Cost of $5 per gge in 2003," http://www.hydrogen.energy.gov/program_records.html.

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9 U.S. Department of Energy (Hydrogen Program), "Record 5038: Hydrogen Cost Competitive on a Cents per Mile Basis – 2006," http://www.hydrogen.energy.gov/program_records.html.

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13 U.S. Department of Energy, *HFCIT Multi-Year Plan*, 3.4-1.

14 National Renewable Energy Laboratory *Distributed Hydrogen Production from Natural Gas Independent Review* (October 2006), 4, retrieved October 5, 2006, from http://www.hydrogen.energy.gov/pdfs/bk40382.pdf.

15 More information on the H2A model can be found at http://www.hydrogen.energy.gov/h2a_analysis.html.

16 U.S. Department of Energy (Hydrogen Program), "Record 5002: DOE Hydrogen Program Solicitation Awardee Announcements," http://www.hydrogen.energy.gov/program_records.html.

17 U.S. Department of Energy (Hydrogen Program), "Record 5032: Overview of IPHE," http://www.hydrogen.energy.gov/program_records.html.

18 U.S. Department of Energy, *Draft Roadmap on Manufacturing R&D for the Hydrogen Economy* (December 2005), retrieved February 4, 2006, from http://www.hydrogen.energy.gov/pdfs/roadmap_manufacturing_hydrogen_economy.pdf.

19 U.S. Government Printing Office, *Federal Register*: August 24, 2006 (Volume 71, Number 164, page 50052-50054), U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Carbon Nanotubes for On-Board Hydrogen Storage Go/No-Go Decision, retrieved October 4, 2006, from http://www.gpoaccess.gov/fr/index.html.

20 National Research Council and National Academy of Engineering, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (Washington, DC: National Academies Press, 2004), http://www.nap.edu/books/030909/632/html.

21 National Research Council, Committee on Review of the FreedomCAR and Fuel Research Program, *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report* (Washington, DC: National Academies Press, 2005), http://www.nap.edu/books/0309097304/html.11.html.

22 U .S. House, 109th Congress, 1st Session, *H.R. 6, Energy Policy Act of 2005* (Public Law No: 109-058), retrieved September 15, 2005, from http://thomas.loc.gov.

23 U.S. Department of Energy (Hydrogen Program), "Record 5028: State of the Union 2003," http://www.hydrogen.energy.gov/program_records.html.

24 U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook 2006: With Projections to 2030*, (February 2006), DOE/EIA-0383(2006), 8, retrieved September 13, 2006, from http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2006).pdf.

25 Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 25, (2006), "Table 1.13 Consumption of Petroleum by End-Use Sector, 1973-2005," 1-17, retrieved August 16, 2006, from http://cta.ornl.gov/data/tedb25/Edition25_Full_Doc.pdf.

26 Ibid., "Table 2.5 Transportation Energy Use by Mode, 2002-2003," (2-7).

27 Ibid., "Table 3.3 U.S. Automobiles and Trucks in Use, 1970-2003," (3-5).

28 Singh M., A. Vyas and E. Steiner, Argonne National Laboratory, *VISION Model: Description of Model Used to Estimate the Impact of Highway Technologies and Fuels on Energy Use and Carbon Emissions to 2050*, (December 2003), ANL/ESD/04-1, retrieved September 27, 2005, from http://www.transportation.anl.gov/pdfs/TA/299.pdf. 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).

29 U.S. Department of Energy, *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs*, *FY 2007 Budget Request*, NREL/TP-620-39684, (March 2006), Table 3-10 Light-Duty Vehicle Market Shares for the Hydrogen Case, p. 3-10, and Table 3-11 Calculation of Petroleum Savings, p. 3-11, retrieved July 26, 2006, from http://www1.eere.energy.gov/ba/pba/gpra_estimates_fy07.html.

30 U.S. Department of Energy (Hydrogen Program), "Record 5018: Reduction in Fuel Consumption with FCVs," http://www.hydrogen.energy.gov/program_records.html.

31 U.S. Department of Energy (Hydrogen Program), "Record 5017: Air Quality and Population," http://www.hydrogen.energy.gov/program_records.html.

32 U.S. Department of Energy, *Annual Energy Outlook 2006* (see note 24), "Table A8: Electricity Supply, Disposition, Prices, and Emissions," (147).

33 U.S. Department of Energy (Hydrogen Program), "Record 5003: Carbon Displacement Using Net-Zero Carbon Sources" http://www.hydrogen.energy.gov/program_records.html.

34 U.S. Department of Energy (Hydrogen Program), "Record 5001: Federal Funding of Hydrogen and Fuel Cell Related Programs," http://www.hydrogen.energy.gov/program_records.html.

35 U.S. Department of Energy (Hydrogen Program), "Record 5019: Japan Government Fuel Cell and Hydrogen Budget," http://www.hydrogen.energy.gov/program_records.html.

36 U.S. Department of Energy (Hydrogen Program), "Record 5022: Current U.S. Hydrogen Production," http://www.hydrogen.energy.gov/program_records.html.

37 U.S. Department of Energy (Hydrogen Program), "Record 5020: Vehicle Carbon Emission Comparisons," http://www.hydrogen.energy.gov/program_records.html.

38 U.S. Department of Energy, *Solar and Wind Technologies for Hydrogen Production: Report to Congress*, ESECS EE-3060, December 2005, retrieved February 3, 2006 from http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/solar_wind_for_hydrogen_dec2005.pdf.

39 U.S. Department of Energy (Hydrogen Program), "Record 5027: Hydrogen Fuel Initiative (White House Press Release)," http://www.hydrogen.energy.gov/program_records.html.

40 U.S. Department of Energy (Hydrogen Program), "*Record 5010: HFI Budget FY 2004-2007,*" http://www.hydrogen.energy.gov/program_records.html.

41 U.S. Department of Energy (Hydrogen Program), "*Record 5004: HFI FY2007 Budget Request for $H_2$ Production*," http://www.hydrogen.energy.gov/program_records.html.

42 U.S. Department of Energy (Hydrogen Program), "*Record 5007: Hydrogen-Related Research at DOE,*" http://www.hydrogen.energy.gov/program_records.html.

43 U.S. Department of Energy (Hydrogen Program), "Record 5016: FutureGen Press Release," http://www.hydrogen.energy.gov/program_records.html.

44 U.S. Department of Energy (Hydrogen Program), "Record 5029: National Academies Press Release," http://www.hydrogen.energy.gov/program_records.html.

45 U.S. Department of Energy Hydrogen Program, "*Record 5021: Fuel Cell System 2005 Cost vs Goal*," http://www.hydrogen.energy.gov/program_records.html.

46 U.S. Department of Energy, *HFCIT Multi-Year Plan*, 3.4-21.

47 U.S. Department of Energy, *HFCIT Multi-Year Plan*, 3.4-2.

48 U.S. House, 109th Congress, 1st Session, *H.R. 3, Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users or SAFETEA-LU* (P.L. 109-59), retrieved January 20, 2006, from http://www.thomas.loc.gov.

49 U.S. Department of Energy Hydrogen Program, "Record 5008: FCV Hydrogen Demand in 2040," http://www.hydrogen.energy.gov/program_records.html.

50 U.S. Department of Energy (Hydrogen Program), "Record 5009: Hydrogen Production from Geothermal," http://www.hydrogen.energy.gov/program_records.html.

51 U.S. Department of Energy (Hydrogen Program), "Record 5024: Hydrogen Production from Hydropower," http://www.hydrogen.energy.gov/program_records.html.

52 U.S. Department of Energy (Hydrogen Program), "Record 5026: Uranium Production and Consumption," http://www.hydrogen.energy.gov/program_records.html.

53 U.S. Department of Energy (Hydrogen Program), "Record 5031: World Nuclear Association," http://www.hydrogen.energy.gov/program_records.html.

# Appendices

A. Sample Scenario for Domestic Hydrogen Production Options and Resource Needs

B. Hydrogen Production and Delivery Pathways

C. Hydrogen Fuel Initiative Budget:  FY 04-FY 07

D. Glossary/Acronyms

E. Contacts, Resources, and Weblinks

# Appendix A: Sample Scenario for Domestic Hydrogen Production Options and Resource Needs

The long-term strategy is to produce hydrogen from a diverse array of carbon-neutral domestic resources, including biomass, coal (with sequestration) wind, solar, and nuclear. The table below provides perspective on the availability of these domestic resources for hydrogen production compared with the amount of hydrogen that may be needed to meet future demand. The total future hydrogen demand used in this example is 64 million metric tons, which represents the amount of hydrogen needed for 300 million fuel cell vehicles.[49] This aggressive scenario is employed here to illustrate how domestic resources could be utilized to provide a large amount of hydrogen. DOE is pursuing other options for replacing oil in the transportation sector, including biofuels and plug-in hybrid electric vehicles, so this level of hydrogen demand for fuel cell vehicles is speculative. In addition, advances in hydrogen production technologies that make the processes more efficient could further reduce the future resource needs.

In the table below, each resource is assumed to provide 20% of the total future hydrogen demand (i.e., almost 13 million tons of hydrogen each), just as an example. The amount of the resource needed to provide this much hydrogen is shown in column 2 ("Needed for Hydrogen") and is compared with estimated resource availability and current consumption. This analysis does not include demand increases for these resources from other sectors (e.g., stationary power, industry, buildings, etc.). Hydrogen production from natural gas is not included in the table to convey that it is not a viable long-term strategy due to concerns of limited supply, volatility, and the demands of other sectors. However, distributed production of hydrogen from natural gas provides a potential near term strategy, and market conditions will determine whether this option is implemented during the initial market penetration of fuel cell vehicles.

| Carbon Neutral Resource | Needed for Hydrogen[a, b] | Availability | Current Consumption | Increase in Consumption with Hydrogen Production (factor times current) |
|---|---|---|---|---|
| **Gasification and Reforming[c]** | | | | |
| Biomass | 140-280 million metric tons/year | Between 512 million dry tons/year[d] and 1.3 billion dry tons/year[e,f] | 190 million metric tons/year[f] | 1.7 - 2.5 |
| Coal (with sequestration) | 110 million metric tons/year | 268 billion tons of estimated recoverable reserves, which is ~54% of 493 billion tons of the demonstrated coal reserve base[g] | 1,100 million metric tons/year (all grades)[h] | 1.1 |
| **Water Electrolysis[i]** | | | | |
| Wind | 200 $GW_e$ | 2,300 GWe (nameplate capacity, not power output)[j] | 10 GWe (installed nameplate capacity, not power output)[k] | 28 |
| Solar | 260 $GW_e$ | 5,400 GWe (capacity, full U.S.)[l] | 371 MWe (installed capacity, SW U.S. only)[m] | 700 |
| Nuclear | 80 $GW_e$ | 345,000 metric tons[n] | 100 GWe[o] | 1.8 |
| **Thermo-Chemical** | | | | |
| Nuclear | 110 GWth | 345,000 metric tons[n] | 310 GWth[p] | 1.3 |

a Shows the amount of each resource needed to produce 20% of the total hydrogen demand of 64 million metric tons/yr (13 million metric tons) in this potential hydrogen fuel cell vehicle scenario. (See note 49—Record 5008—for calculation of 64 million metric tons.)

b The National Renewable Energy Laboratory *H2A Production Model*, version 1.0.9, was used to determine the amount of hydrogen needed for each advanced technology (see note 11).

c 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.

d Walsh, M.E. et al., *Biomass Feedstock Availability in the United States: 1999 State Level Analysis*, (2000), retrieved September 29, 2005, from http://bioenergy.ornl.gov/resourcedata/index.html.

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

f Perlack, R. D. et al., *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, (April 2005), performed by Oak Ridge National Laboratory for the U.S. Department of Agriculture and U.S. Department of Energy, ORNL/TM-2005/66, DOE/GO-102995-2135, retrieved September 29, 2005, from http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf.

g U.S. Department of Energy, Energy Information Administration, *Annual Coal Report – 2004*, (November 2005), DOE/EIA-0584(2004), Table 15: "Recoverable Coal Reserves at Producing Mines, Estimated Recoverable Reserves, and Demonstrated Reserve Base by Mining Method, 2004," 31, retrieved January 23, 2006 from http://www.eia.doe.gov/cneaf/coal/page/acr/table15.html

h U.S. Department of Energy, Energy Information Administration, *Quarterly Coal Report: July – September 2005*, (December 2005), DOE/EIA-0121(2005/03Q), Table 28: "U.S. Coal Consumption by End-Use Sector 1999-2005, 32, retrieved January 23, 2006 from http://www.eia.doe.gov/cneaf/coal/quarterly/html/t28p01p1.html.

i 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 or up to 68 million tons of hydrogen if estimates of undiscovered accessible resources are considered (see note 50—Record 5009). Undeveloped hydropower resources and upgrades to existing hydroelectric plants could supply an additional 15 million tons of hydrogen per year (see note 51—Record 5024).

j Elliott, D.L. and M.N. Schwartz., *Wind Energy Potential in the United States*, (Richland, WA: Pacific Northwest National Laboratory, September 1993), PNL-SA-23109, retrieved September 29, 2005, from http://www.nrel.gov/wind/wind_potential.html.

k U.S. Department of Energy and National Renewable Energy Laboratory, "United States 2005 Installed Wind Power Capacity," (as of June 30, 2006), retrieved October 23, 2006 from http://www.eere.energy.gov/windandhydro/windpoweringamerica/wind_installed_capacity.asp.

l U.S. Department of Energy (Hydrogen Program), "Record 5006: Solar Resources in the U.S.," http://www.hydrogen.energy.gov/program_records.html.

m Land and Water Fund of the Rockies, *Renewable Energy Atlas of the West*, (Boulder, CO: July 2002), 10, retrieved September 29, 2005, from http://www.energyatlas.org.

n Uranium is sold on a very open, competitive market. Annual U.S. production provides less than 4-5% of U.S. needs under the current once-through fuel cycle approach (see note 52—Record 5026). However, nuclear systems can be configured for greater fuel use efficiency, even to the point of extending a known supply by a factor of 50 (see note 53—Record 5031). In the extremely unlikely event that U.S. uranium resources became the sole supply for U.S. reactors, they could be extended to last for over a thousand years.

o Nuclear Regulatory Commission, *2005-2006 Edition Information Digest*, NUREG-1350, Volume 17, (July 2005), 23, retrieved January 24, 2006 from http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/v17/sr1350v17.pdf.

p The nuclear thermo-chemical route to hydrogen production is based on the use of high-temperature reactor technology which is under development to generate the higher temperatures needed (800-1000°C). The 310 GWth is the amount of thermal energy equivalent currently generated by today's conventional nuclear energy that is in service for electricity production (100 GWe divided by 32% thermal efficiency).

# Appendix B. Hydrogen Production and Delivery Pathways*

The ultimate goal is for hydrogen to be produced and delivered utilizing several feedstocks, processing methods, and delivery options at a variety of scales ranging from large central production to very small local production, depending on what makes the most economic and logistical sense for that location. 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 tradeoffs each offer. From this understanding, we will continue to refine the DOE research and development plan for hydrogen production and delivery to ensure that viable, cost-effective options become available for both the short term and long term.

This Appendix contains well-to-wheels (WTW) analysis results comparing current (2005) gasoline internal combustion engine (ICE) and hybrid vehicles and hydrogen fuel cell vehicles (FCVs). It includes several potential options for hydrogen production and delivery. Two time frames are examined for the hydrogen cases. The "current" cases represent 2005 technology in the laboratory; however, this technology has not been validated at full scale. The "future" cases examine 2015 potential technology for distributed production of hydrogen at refueling stations and 2030 for central hydrogen production options. Projected costs are also presented for the hydrogen FCV cases.

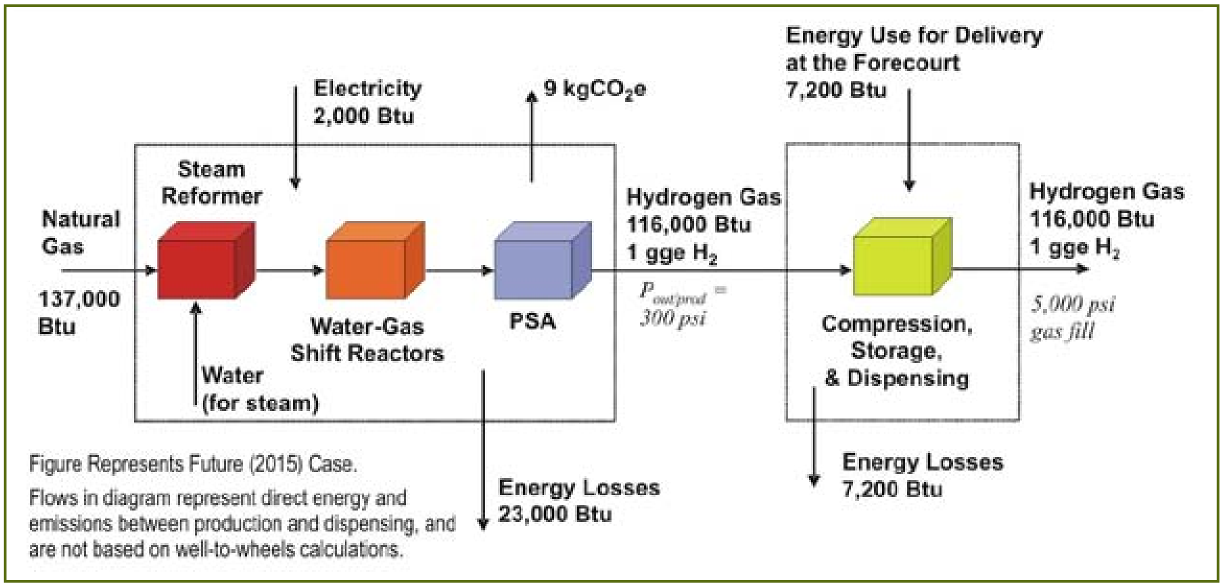
The hydrogen production and delivery analyses presented here utilize the H2A Production and Delivery model approach and tools (which can be accessed at www.hydrogen.energy.gov/h2a_analysis.html). The assumptions for each production technology-specific case are provided to clarify the basis for and data used in the analyses.

For the central hydrogen production cases, two delivery technologies are analyzed. For the current cases it is assumed that the hydrogen is liquefied and transported by cryogenic liquid trucks to the forecourt station where it is stored, and then vaporized under pressure and dispensed as a high pressure gas to the FCV. For the 2030 future cases, it is assumed that a hydrogen pipeline infrastructure is available to transport the hydrogen to the forecourt. The hydrogen is first compressed from its assumed production pressure of 300 psi to a pipeline pressure of 1,000 psi. At the forecourt it is further compressed, stored, and charged as a high pressure gas to the FCV at a 5,000 psi fill. The cost of hydrogen delivery used for the current central hydrogen production cases is $3.50/gge of hydrogen. This includes liquefaction, truck transport, and forecourt operations. This is based on the H2A Delivery Scenario model under development. This model is available at www.hydrogen.energy.gov. The cost of hydrogen delivery used for the future central hydrogen production cases is $1.00/gge of hydrogen. This includes compression, pipeline transport, and forecourt operations of compression, storage, and dispensing. This is based on the Program's targeted cost for hydrogen delivery technology. Note that all costs are expressed in real 2005 dollars.

* For additional information, see Chapter 5 and Appendix E of the National Research Council report *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (Washington, DC: National Academies Press, 2004).

## Figure B-1. Distributed Hydrogen Production via Steam Methane Reforming

Distributed production of hydrogen from natural gas utilizes small scale steam methane reforming technology. The advantages of distributed hydrogen production are the production unit can be located at the consumer refueling site, the unit capacity can be tailored to the site's fueling requirements, and this approach eliminates the need for an extensive hydrogen delivery infrastructure. This process may be the most viable for introducing hydrogen as an energy carrier since it requires less capital investment for the smaller hydrogen volumes that are needed in the early stages of hydrogen technology adoption.




| Well-to-Wheels Energy and Greenhouse Gas Emissions Data | | | | |
|---|---|---|---|---|
| | Current (2005) Gasoline ICE Vehicle | Current (2005) Gasoline Hybrid Electric Vehicle | Current (2005) Distributed SMR - FCV | Future (2015) Distributed SMR - FCV |
| Well-to-Wheels Total Energy Use (Btu/mile) | 5,900 | 4,200 | 3,700 | 2,800 |
| Well-to-Wheels Petroleum Energy Use (Btu/mile) | 5,300 | 3,800 | 40 | 40 |
| Well-to-Wheels Greenhouse Gas Emissions ($gCO_2e$/mile) | 470 | 340 | 260 | 200 |
| Cost of Hydrogen ($/gge, Delivered) | | | 3.10 | 2.00 |

*This analysis is based on the best available technology in the laboratory. Currently, it has not been validated through demonstration.*

Notes: Distributed Hydrogen Production via Steam Methane Reforming

1. Source: Well-to-wheels energy, petroleum, and greenhouse gas emissions information from the Argonne National Laboratory GREET model, Version 1.7. Well-to-wheels values represent primary fuel production, electricity production, hydrogen production, hydrogen compression, and hydrogen dispensing. Fossil resource exploration and equipment manufacture are not included.
2. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the current (2005) case are from the H2A model cases (Version 1.0.9) modified to reflect the Hydrogen Program 2005 cost goals as of November 2005. Capacity of plant represented here is 1,500 kg/day.
3. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the future (2015) case are from the H2A model cases modified to reflect the Hydrogen Program 2015 cost goals as of November 2005.
4. Basis is 1 kg of hydrogen, dispensed from filling station for 5,000 psi fills. A kg of hydrogen contains approximately the same amount of energy as one gallon of gasoline, or one gallon of gasoline equivalent (gge).
5. Diagram is for future (2015) case, showing feedstock and energy consumption levels required to meet technology cost goals. Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.
6. Costs include hydrogen production, compression, storage, and dispensing to vehicle. Cost assumes that small-scale steam methane reforming technology is added to an existing fueling station.

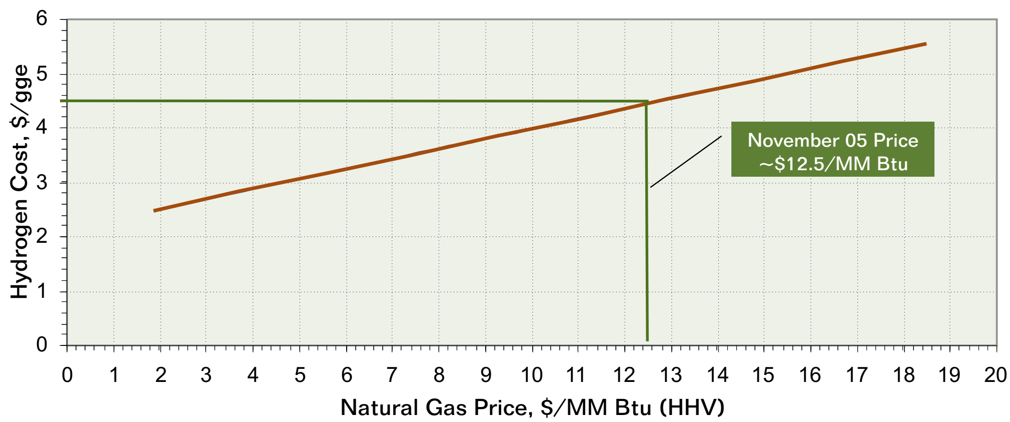
7. Efficiency results are presented in terms of lower heating value (LHV) of hydrogen.
8. The efficiency of the electric forecourt compressor, which raises the pressure of gaseous hydrogen for 5,000 psi fills, is 94%.
9. The operating capacity factor of the forecourt station is 70%. This value accounts for on-stream availability as well as consumer demand variations between week days/weekends and winter/summer.
10. Natural gas feedstock prices are based on the 2015 projections for industrial natural gas by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Prices shown in table are in 2005 $. Feedstock is inflated at 1.9%/year for the 20-year operating life of the plant.
11. Electricity is consumed by the process for production and compression operations. Electricity prices are based on the 2015 projections for commercial-rate electricity by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Prices shown in table are in 2005 $. Electricity is inflated at 1.9%/year for the 20-year operating life of the plant.
12. Capital cost of current (2005) and future (2015) cases are $1.40/kg hydrogen and $0.60/kg hydrogen, respectively.
13. Cost of hydrogen is the minimum required to obtain a 10% internal rate of return after taxes on the capital investment.
14. The data relevant to the Distributed SMR technology diagram above are provided in the table below.

| | Current (2005) Distributed SMR - FCV | Future (2015) Distributed SMR - FCV |
|---|---|---|
| Natural Gas Feedstock Price ($/million Btu LHV) | 5.24 | 5.24 |
| Natural Gas Feedstock Price ($/thousand scf) | 5.15 | 5.15 |
| Energy in Natural Gas Feedstock (Btu) | 165,000 | 137,000 |
| Electricity Price ($/kWh) | 0.076 | 0.076 |
| Electricity to Process (Btu) | 2,000 | 2,000 |
| Energy Losses from Process (Btu) | 51,000 | 23,000 |
| Pressure of Hydrogen from Production (psi) | 300 | 300 |
| Energy Use for Delivery at Forecourt (Btu) | 7,200 | 7,200 |
| Energy Use for Delivery Transport (Btu) | N/A–Forecourt Production | N/A–Forecourt Production |
| Hydrogen Dispensing Fill Pressure (psi) | 5,000 | 5,000 |
| Plant Gate Energy Use Including Feedstock (Btu) | 167,000 | 139,000 |
| Production Process Efficiency | 69% | 83% |
| Pathway Efficiency | 66% | 79% |
| Greenhouse Gas Emissions from Production (lb/gge of hydrogen produced) | 24 | 20 |

## Understanding Effects of Feedstock Volatility

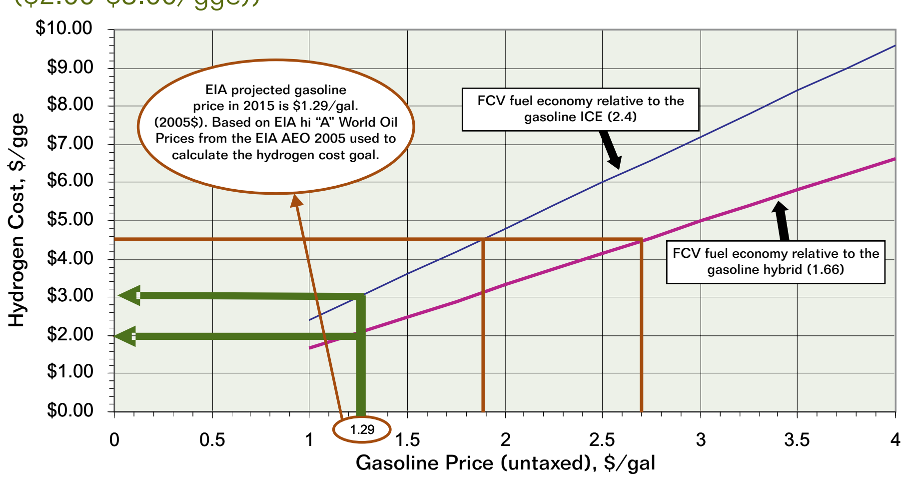
Distributed natural gas/renewable liquid reforming and on-site electrolysis (promoting renewable electricity) strategies provide advantages as potential near-term hydrogen production options because they obviate the need for a new delivery infrastructure. Current delivery methods (high pressure tube trailers and "liquid" trucks) are very energy intensive and not cost effective for distances over 100 miles. The distributed reforming approach is an enabling technology to produce hydrogen not only from natural gas, but from a portfolio of options such as methanol, ethanol and other renewable liquids. In the longer term, when diverse domestic resources are used, volatility of hydrogen price should not be an issue. However, natural gas prices are known to be volatile and this is an important consideration for planning. The chart below shows this sensitivity.

### Hydrogen Production Cost from Distributed Natural Gas Versus Sensitivity to Natural Gas Price (HHV)




For example, using a November 2005 data point for industrial natural gas price ($12.50 per million Btu), hydrogen would currently cost $4.50 per gallon-gasoline-equivalent (gge). This cost is calculated using the H2A financial model which calculates hydrogen costs based on the current technology development status. The H2A model is a cash flow model that allows us to understand the cost of various hydrogen production and delivery pathways on a consistent basis. This portfolio analysis tool provides a levelized cost of hydrogen for a given rate of return (input) and accounts for capital costs, construction time, taxes, depreciation, O&M, inflation, and feedstock prices. See http://www.hydrogen.energy.gov/h2a_anaylsis.html. As shown in the chart below, hydrogen at $4.50/gge would make hydrogen fuel cell vehicles competitive on a cents per mile basis with gasoline vehicles (ICE) at gasoline prices of $1.90/gge (untaxed) and gasoline hybrid-electric vehicles at gasoline prices of $2.70/gge (untaxed).

### Model for Hydrogen Cost Goal (Yielding Equivalent $/ml. for the Consumer ($2.00-$3.00/gge))

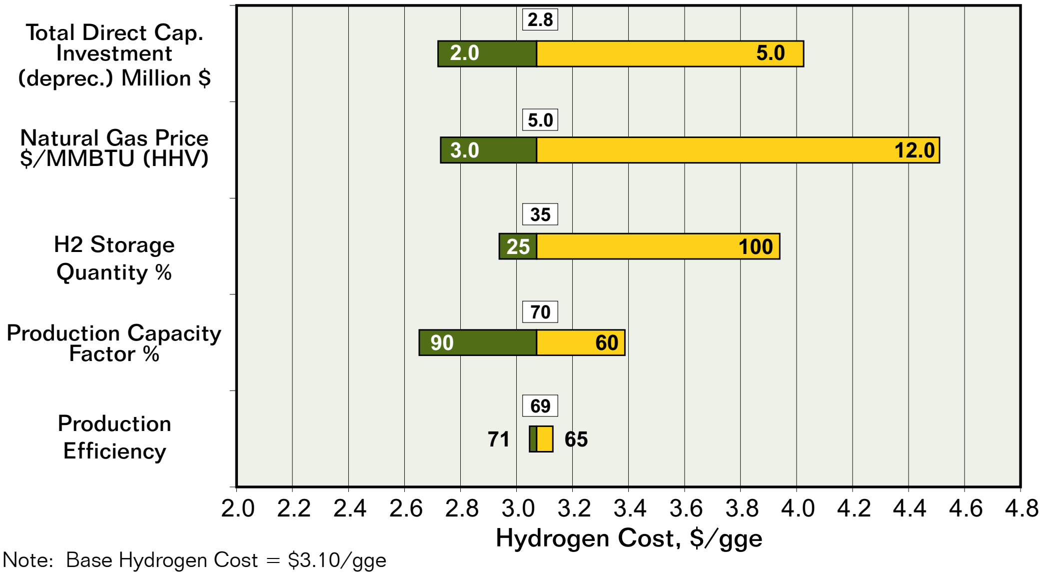



Note: The FCV fuel economy ratios relative to the gasoline ICE and hybrid were obtained from the NRC report: *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, p.66.

The impact of the volatility of natural gas prices will continue to be evaluated to ensure the viability of this hydrogen production pathway. Feedstock price volatility will significantly influence investment decisions.

The chart below shows the major variables that influence natural gas-based hydrogen costs.

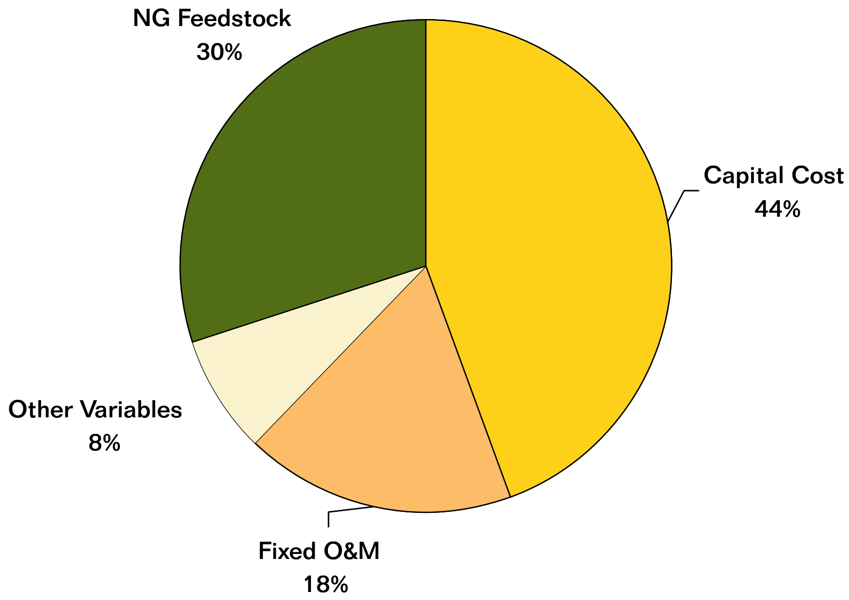
### Sensitivity Analyses for Distributed Hydrogen Production from Natural Gas (current estimate is $3.10/gge with 2005 EIA High A estimate)




Note: Base Hydrogen Cost = $3.10/gge

The pie chart below shows the composition of costs contributing to the current estimate of producing hydrogen from distributed natural gas. This estimate is based on the best available research, projected to high volume, but not yet validated under real-world operating conditions by the Program's Technology Validation Sub-Program. This estimate is based on the 2005 EIA High A estimate for natural gas in 2015.

### Cost Breakdown of Hydrogen from Distributed Natural Gas ($3.10/gge)



## Figure B-2. Distributed Hydrogen Production from Wind

Wind power is currently utilized as a renewable power technology for generating electricity. Combining this electricity with water electrolysis, wind can provide hydrogen with few emissions and with very low consumption of petroleum. Wind-generated electricity can be sent to distributed electrolyzers via the electric grid. The petroleum energy use and resultant $CO_2$ emissions from this process are associated with hydrogen compression at the forecourt, as well as the use of grid electricity. Grid electricity supplements the electricity from wind to increase the capacity factor on the electrolyzer.

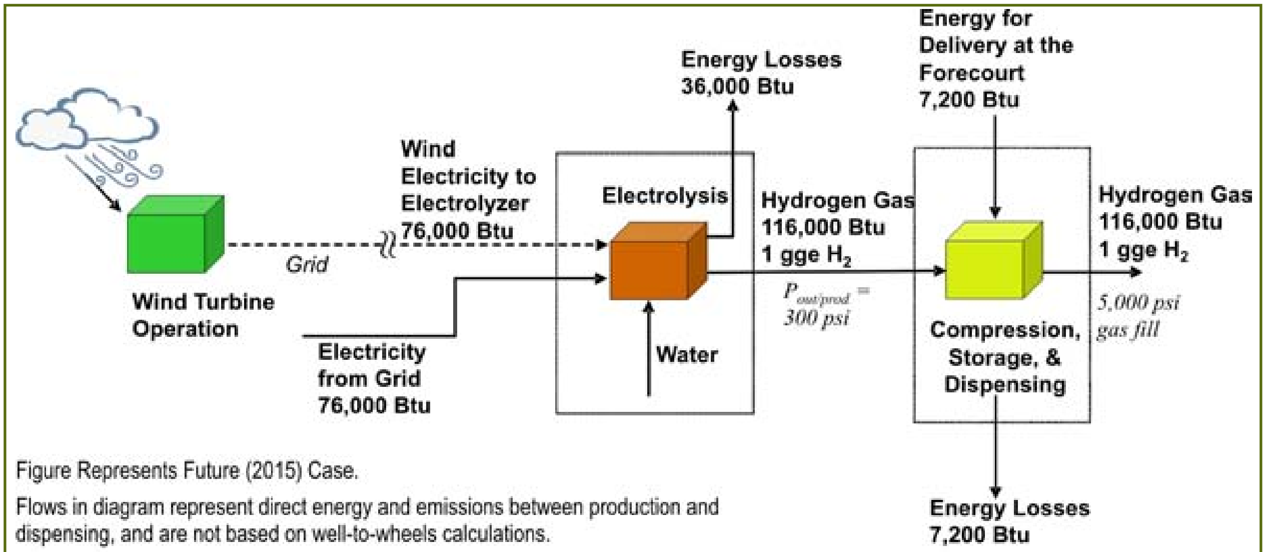



Figure Represents Future (2015) Case.

Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.

| Well-to-Wheels Energy and Greenhouse Gas Emissions Data | | | | |
|---|---|---|---|---|
| | Current (2005) Gasoline ICE Vehicle | Current (2005) Gasoline Hybrid Electric Vehicle | Current (2005) Distributed Electrolysis Using Wind/ Grid - FCV | Future (2015) Distributed Electrolysis Using Wind Energy - FCV |
| Well-to-Wheels Total Energy Use (Btu/mile) | 5,900 | 4,200 | 6,200 | 4,500 |
| Well-to-Wheels Petroleum Energy Use (Btu/mile) | 5,300 | 3,800 | 130 | 100 |
| Well-to-Wheels Greenhouse Gas Emissions ($gCO_2e$/mile) | 470 | 340 | 490 | 310 |
| Cost of Hydrogen ($/gge, Delivered) | | | 5.70 | 3.10 |

*This analysis is based on the best available technology in the laboratory. Currently, it has not been validated through demonstration.*

Notes: Distributed Hydrogen Production from Wind

1. Source: Well-to-wheels energy, petroleum, and greenhouse gas emissions information from the Argonne National Laboratory GREET model, Version 1.7. Well-to-wheels values represent primary fuel production, electricity production, hydrogen production, hydrogen compression, and hydrogen dispensing. Fossil resource exploration and equipment manufacture are not included.
2. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the current (2005) case are from the National Renewable Energy Laboratory and the H2A model, Version 1.0.9 for a forecourt electrolysis facility. Capacity of plant represented here is 1,500 kg/day.
3. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the future (2015) case are from the H2A advanced forecourt case modified to include a $250/kW installed capital cost for the electrolyzer and $0.038/kWh electricity price.
4. Basis is 1 kg of hydrogen, dispensed from filling station for 5,000 psi fills. A kg of hydrogen contains approximately the same amount of energy as one gallon of gasoline, or one gallon of gasoline equivalent (gge).
5. Diagram is for future (2015) case, showing feedstock and energy consumption levels required to meet technology cost goals. Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.
6. The petroleum use and resultant GHG emissions are associated with the grid electricity for compression, and to supplement the wind-based electricity for electrolysis.

7. Energy from incoming wind is not included in the overall energy balance, although the wind-generated electricity is. Grid efficiency loss = 7.3% as per assumption in ANL GREET model.
8. Diagram is for future (2015) case. Cost of future (2015) case assumes electricity assistance provided by grid to maintain capacity factor at 70%; the electricity to the electrolyzer is assumed to be 50% wind, 50% grid. Cost of current (2005) case also assumes electricity assistance provided by grid to maintain capacity factor at 70%; the electricity to the electrolyzer is assumed to be 30% wind, 70% grid. Wind energy is assumed to be transported via the electrical grid to the distributed electrolyzer.
9. Current (2005) electrolyzer uses 53.4 kWh of electricity per kg of hydrogen generated. Future (2015) electrolyzer uses 44.5 kWh/kg. The LHV electrolyzer efficiencies for the current (2005) and future (2015) cases are 64% and 76%, respectively.
10. Installed electrolyzer capital cost for 2005 and 2015 cases is $730/kW and $250/kW, respectively.
11. Efficiency results are presented in terms of lower heating value (LHV) of hydrogen.
12. The efficiency of the electric forecourt compressor, which raises pressure of the gaseous hydrogen for 5,000 psi fills, is 94%.
13. The operating capacity factor of the production unit is 70%.
14. Electricity is consumed by the process for compression and electrolyzer operations. Electricity prices for the current (2005) case is based on the 2005 projection for industrial-rate electricity by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Electricity price for the future (2015) case is $0.038/kWh. Prices shown in table are in 2005 $. Electricity is inflated at 1.9%/year for the 20-year operating life of the plant. It is assumed that both grid electricity and wind electricity is available at the same price.
15. Cost of hydrogen is the minimum required to obtain a 10% internal rate of return after taxes on the capital investment.
16. The data relevant to the Distributed Hydrogen Production from Wind technology diagram above are provided in the table below.

| | Current (2005) Distributed Electrolysis Using Wind/Grid - FCV | Future (2015) Distributed Electrolysis Using Wind Energy - FCV |
|---|---|---|
| **Feedstock Price ($/million Btu)** | N/A - Wind Energy | N/A - Wind Energy |
| **Energy in Feedstock (Btu)** | N/A - Wind Energy | N/A - Wind Energy |
| **Grid Electricity Consumed (kWh)** | 40 | 24 |
| **Electricity Price ($/kWh)** | 0.052 | 0.038 |
| **Electricity to Process (Btu)** | 182,000 | 152,000 |
| **Energy Losses from Process (Btu)** | 66,000 | 36,000 |
| **Pressure of Hydrogen from Production (psi)** | 300 | 300 |
| **Energy Use for Delivery at the Forecourt (Btu)** | 7,200 | 7,200 |
| **Energy Use for Delivery Transport (Btu)** | N/A - Forecourt Production | N/A - Forecourt Production |
| **Hydrogen Dispensing Fill Pressure (psi)** | 5,000 | 5,000 |
| **Plant Gate Energy Use Including Feedstock (Btu)** | 182,000 | 152,000 |
| **Production Process Efficiency** | 64% | 76% |
| **Pathway Efficiency** | 61% | 73% |

## Figure B-3. Centralized Hydrogen Production from Wind

Wind power is currently utilized as a renewable power technology for generating electricity. Combining this electricity with water electrolysis, wind can provide hydrogen with few emissions and with very low consumption of petroleum. Grid electricity supplements the electricity from wind to increase the capacity factor of the electrolyzer for the future case. The petroleum energy use and resultant $CO_2$ emissions from this process are associated with hydrogen delivery, as well as the use of grid electricity for the future case.

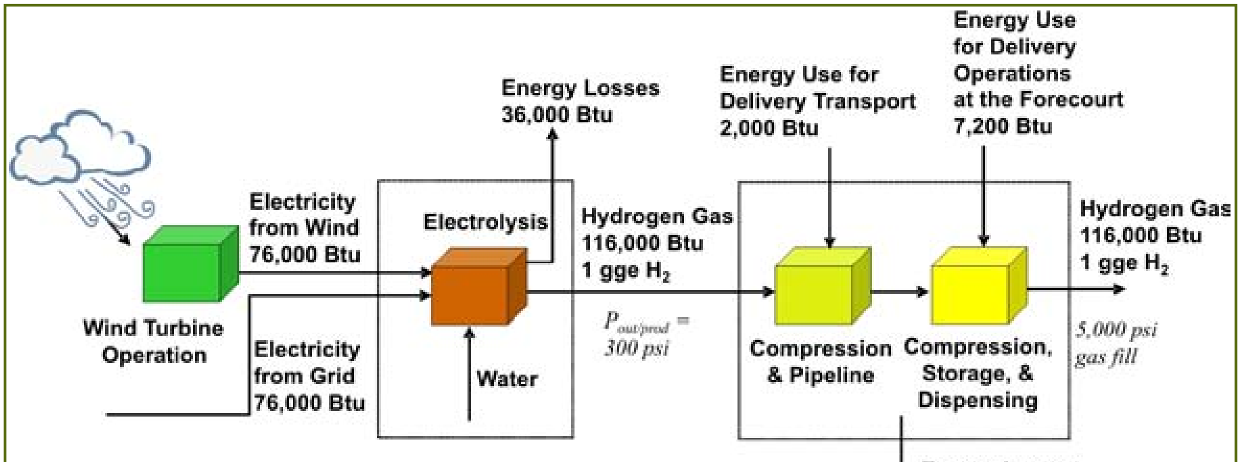



Figure Represents Future (2030) Case.

Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.

| Well-to-Wheels Energy and Greenhouse Gas Emissions Data | | | | |
|---|---|---|---|---|
| | Current (2005) Gasoline ICE Vehicle | Current (2005) Gasoline Hybrid Electric Vehicle | Current (2005) Central Electrolysis Using Wind - FCV | Future (2030) Central Electrolysis Using Wind/Grid - FCV |
| Well-to-Wheels Total Energy Use (Btu/mile) | 5,900 | 4,200 | 3,800 | 4,700 |
| Well-to-Wheels Petroleum Energy Use (Btu/mile) | 5,300 | 3,800 | 20 | 100 |
| Well-to-Wheels Greenhouse Gas Emissions ($gCO_2e$/mile) | 470 | 340 | 50 | 50 |
| Cost of Hydrogen ($/gge, Delivered) | | | 9.50 | 2.70 |

*This analysis is based on the best available technology in the laboratory. Currently, it has not been validated through demonstration.*

Notes: Centralized Hydrogen Production from Wind

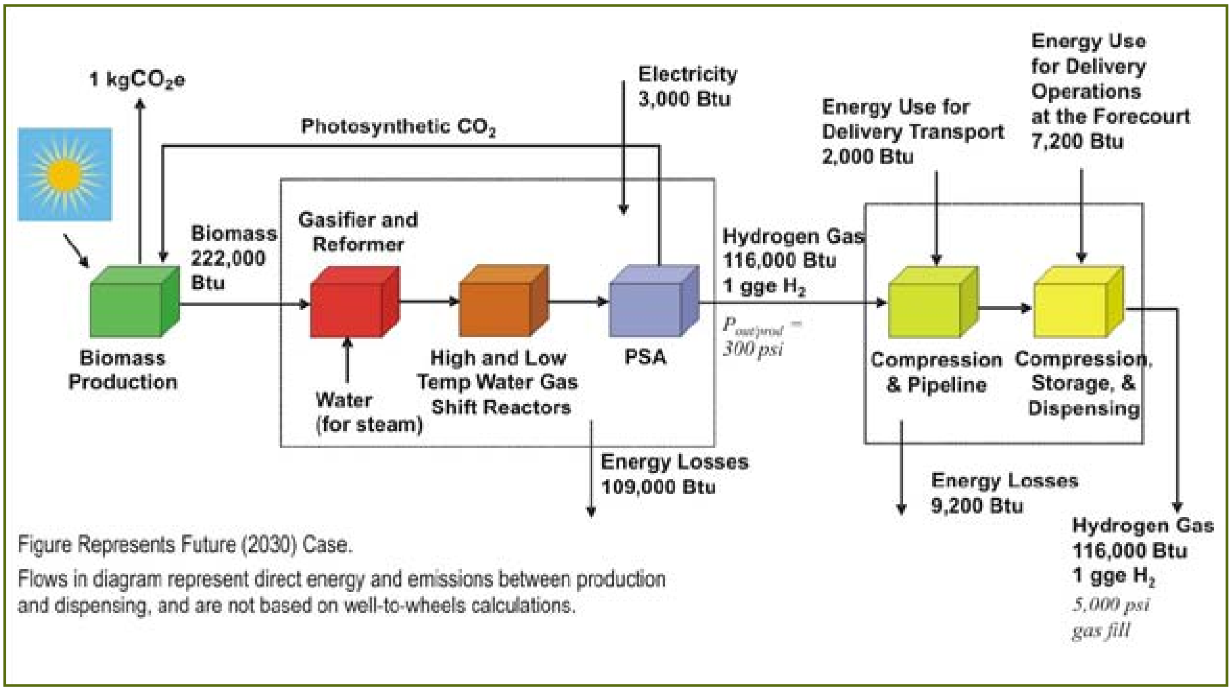
1. Source: Well-to-wheels energy, petroleum, and greenhouse gas emissions information from the Argonne National Laboratory GREET model, Version 1.7. Well-to-wheels values represent primary fuel production, electricity production, hydrogen production, and hydrogen delivery. Fossil resource exploration and equipment manufacture is not included.
2. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the current (2005) cases are from the National Renewable Energy Laboratory and the H2A model, Version 1.0.9 for a 125,000 kg/day capacity wind electrolysis facility.
3. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the future (2030) case is from the H2A model cases modified to reflect the Hydrogen Program 2015 cost goals as of November 2005.
4. Basis is 1 kg of hydrogen, dispensed from filling station for 5,000 psi fills. A kg of hydrogen contains approximately the same amount of energy as one gallon of gasoline, or one gallon of gasoline equivalent (gge).
5. Diagram is for future (2030) case, showing feedstock and energy consumption levels required to meet technology cost goals. Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.

6. Cost of 2030 case assumes electricity assistance provided by grid to maintain capacity factor at 97%; the electricity to the electrolyzer is assumed to be 50% wind, 50% grid. Current (2005) case uses only wind-generated electricity, with an electrolyzer capacity factor of 41%. While the higher capacity factor is required for an economic future (2030) case, it results in higher well-to-wheels total energy use and greenhouse gas emissions. The greehouse gas emissions are slightly higher for the future (2030) case, although rounding to significant figures hides this effect. In the future (2030) case, grid electricity is purchased at the avoided price of $0.03/kWh. Avoided cost estimates the incremental cost of fuel and capacity displaced by a unit of the specified resource and more accurately reflects the as-dispatched energy value than comparison to the levelized cost of other individual technologies. See http://www.eia.doe.gov/oiaf/aeo/electricity.html for more details.
7. The price of electricity produced from wind in the current (2005) case was calculated from the current (2005) central wind electrolysis H2A case and assumed to be the price at which wind electricity was produced in the model. In the future case (2030) it was assumed the grid and wind electricity prices were the same (at $0.03/kWh).
8. The petroleum use and resultant GHG emissions are associated with the grid electricity for delivery, as well as for grid assistance in the future (2030) case. Fossil-based power plants generating grid electricity for the future (2030) case are assumed to sequester carbon emissions at a rate of 85%.
9. Energy from incoming wind was not included in the overall energy balance, although the wind-generated electricity is.
10. The hydrogen delivery in the current (2005) case assumes liquid hydrogen delivery by truck from a central plant located 76 miles from the forecourt station. Liquefier efficiency is 77.4%. Truck fuel consumption is 6 mi/gallon. Data was obtained from the H2A Delivery Scenario Model and GREET. The future (2030) case assumes hydrogen pipeline delivery over 76 miles. Delivery costs include necessary compression and/or liquefaction equipment.
11. Cost of hydrogen delivery for the current (2005) and future (2030) cases is assumed to be $3.50/kg and $1.00/kg, respectively.
12. Future (2030) case assumes pipeline compressed gas delivery to the forecourt station. Pipeline energy use calculated using the H2A Scenario Model.
13. The efficiency of the electric forecourt compressor, which raises the pressure of the gaseous hydrogen for 5,000 psi fills, is 94%.
14. For the current (2005) case, hydrogen is assumed to be received at the forecourt as a liquid and dispensed as a gas for 5,000 psi fills. For the future (2030) case, hydrogen is assumed to be received at the forecourt as gaseous hydrogen at 250 psi by pipeline and dispensed for 5,000 psi fills. The cost of dispensing is included in the delivery cost.
15. Current (2005) electrolyzer uses 53.4 kWh of electricity per kg of hydrogen generated. Future (2030) electrolyzer uses 44.5 kWh/kg. The LHV electrolyzer efficiencies for the current (2005) and future (2030) cases are 64% and 76%, respectively.
16. Installed electrolyzer capital cost for 2005 and 2030 cases is $800/kW and $180/kW, respectively.
17. Efficiency results are presented in terms of lower heating value (LHV) of hydrogen.
18. Cost of hydrogen is the minimum required to obtain a 10% internal rate of return after taxes on the capital investment.
19. The data relevant to the Centralized Hydrogen Production from Wind technology diagram above are provided in the table below.

| | **Current (2005) Central Electrolysis Using Wind - FCV** | **Future (2030) Central Electrolysis Using Wind/Grid - FCV** |
|---|---|---|
| **Feedstock Price ($/million Btu)** | N/A - Wind Energy | N/A - Wind Energy |
| **Energy in Feedstock (Btu)** | N/A - Wind Energy | N/A - Wind Energy |
| **Grid Electricity Consumed (kWh)** | N/A - Wind Energy | 22 |
| **Grid Electricity Price ($/kWh)** | N/A - Wind Energy | 0.030 |
| **Wind Electricity Price ($/kWh)** | 0.049 | 0.030 |
| **Electricity to Process (Btu)** | 182,000 | 152,000 |
| **Energy Losses from Process (Btu)** | 66,000 | 36,000 |
| **Pressure of Hydrogen from Production (psi)** | 300 | 300 |
| **Energy Use for Delivery Forecourt Operations (Btu)** | Negligible | 7,200 |
| **Energy Use for Delivery Transport (Btu)** | 34,000 | 2,000 |
| **Hydrogen Dispensing Fill Pressure (psi)** | 5,000 | 5,000 |
| **Plant Gate Energy Use Including Feedstock (Btu)** | 182,000 | 152,000 |
| **Production Process Efficiency** | 64% | 76% |
| **Pathway Efficiency** | 54% | 72% |

## Figure B-4. Centralized 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 the conversion to hydrogen. In this diagram, we show the $CO_2$ being recycled by photosynthesis into additional biomass. It would be possible to capture and sequester the $CO_2$ from the PSA unit resulting in a hydrogen process with net negative $CO_2$ emissions. The petroleum energy use and the $CO_2$ emissions from this process are associated with operations related to growing the biomass and making it available to the hydrogen process, production electricity use, and hydrogen delivery.




**Well-to-Wheels Energy and Greenhouse Gas Emissions Data**

| | Current (2005) Gasoline ICE Vehicle | Current (2005) Gasoline Hybrid Electric Vehicle | Current (2005) Biomass Gasification - FCV | Future (2030) Biomass Gasification - FCV |
|---|---|---|---|---|
| Well-to-Wheels Total Energy Use (Btu/mile) | 5,900 | 4,200 | 6,600 | 3,600 |
| Well-to-Wheels Petroleum Energy Use (Btu/mile) | 5,300 | 3,800 | 200 | 100 |
| Well-to-Wheels Greenhouse Gas Emissions ($gCO_2e$/mile) | 470 | 340 | 190 | 30 |
| Cost of Hydrogen ($/gge, Delivered) | | | 5.10 | 2.40 |

*This analysis is based on the best available technology in the laboratory. Currently, it has not been validated through demonstration.*

Notes: Centralized Hydrogen Production from Biomass Gasification

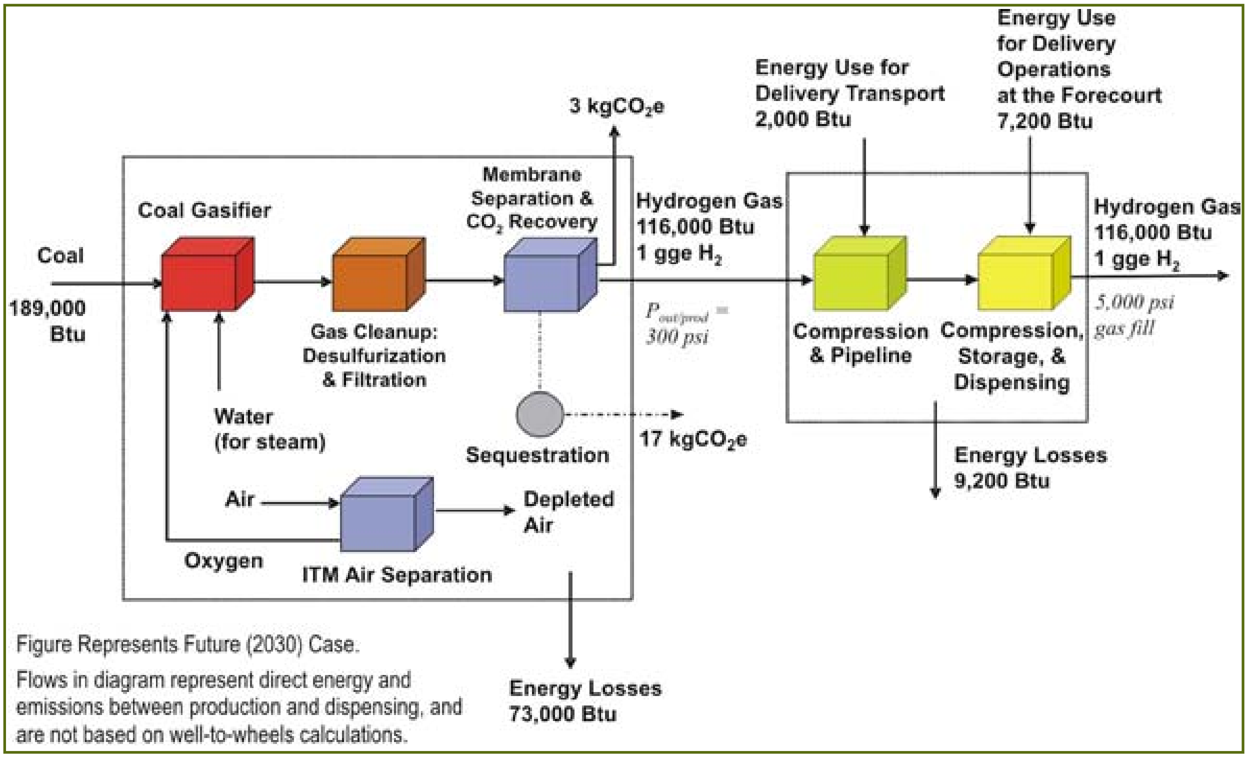
1. Source: Well-to-wheels energy, petroleum, and greenhouse gas emissions information from the Argonne National Laboratory GREET model, Version 1.7. Well-to-wheels values represent primary fuel production, electricity production, hydrogen production, and hydrogen delivery. Fossil resource exploration and equipment manufacture are not included.
2. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the current (2005) case are from the National Renewable Energy Laboratory and the H2A model, Version 1.0.9, for a Central Biomass production facility with a capacity of 155,000 kg/day.
3. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the future (2030) case are from the H2A model cases modified to reflect the Hydrogen Program 2015 cost goals as of November 2005.
4. Basis is 1 kg of hydrogen, dispensed from filling station for 5,000 psi fills. A kg of hydrogen contains approximately the same amount of energy as one gallon of gasoline, or one gallon of gasoline equivalent (gge).

5. Diagram is for future (2030) case, showing feedstock and energy consumption levels required to meet technology cost goals. Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.
6. The petroleum use and resultant GHG emissions are associated with growing the biomass, and the grid electricity for delivery. Fossil-based power plants generating grid electricity for the future (2030) case are assumed to sequester carbon emissions at a rate of 85%.
7. Biomass is assumed to be woody biomass, most likely obtained from a residue source (e.g., urban trimmings) or energy crops.
8. The hydrogen delivery in the current (2005) case assumes liquid hydrogen delivery by truck from a central plant located 76 miles from the forecourt station. Liquefier efficiency is 77.4%. Truck fuel consumption is 6 mi/gallon. Data were obtained from the H2A Delivery Scenario Model and GREET. The future (2030) case assumes hydrogen pipeline delivery over 76 miles. Delivery costs include necessary compression and/or liquefaction equipment.
9. Cost of hydrogen delivery for the current (2005) and future (2030) cases is assumed to be $3.50/kg and $1.00/kg, respectively.
10. For the current (2005) case, hydrogen is assumed to be received at the forecourt as a liquid and dispensed as a gas for 5,000 psi fills. For the future (2030) case, hydrogen is assumed to be received at the forecourt as gaseous hydrogen at 250 psi by pipeline and dispensed for 5,000 psi fills. The cost of these forecourt operations is included in the delivery cost.
11. Efficiency results are presented in terms of lower heating value (LHV) of hydrogen.
12. Future (2030) case assumes pipeline compressed gas delivery to the forecourt station. Pipeline energy use calculated using the H2A Delivery Models.
13. The efficiency of the electric forecourt compressor, which raises the pressure of the gaseous hydrogen for 5,000 psi fills, is 94%.
14. The operating capacity factor of the production plant is 90%.
15. Electricity is consumed by the process for plant operations and delivery. Electricity prices are based on the 2015 projections for industrial-rate electricity by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Prices shown in table are in 2005 $. Electricity is inflated at 1.9%/year for the 40-year operating life of the plant.
16. The levelized capital cost for the current (2005) and future (2030) cases are $0.49/kg hydrogen and $0.47/kg of hydrogen; capital cost estimate increases because of increased contingency to account for uncertainty in project projections and technology in the 2030 timeframe.
17. Cost of hydrogen is the minimum required to obtain a 10% internal rate of return after taxes on the capital investment.
18. The data relevant to the Centralized Hydrogen Production from Biomass Gasification technology diagram above are provided in the table below.

| | Current (2005) Biomass Gasification - FCV | Future (2030) Biomass Gasification - FCV |
|---|---|---|
| Biomass Feedstock Price ($/million Btu LHV) | 2.26 | 2.26 |
| Biomass Feedstock Price ($/bone dry ton) | 38.00 | 38.00 |
| Energy in Biomass Feedstock (Btu) | 252,000 | 222,000 |
| Electricity Price ($/kWh) | 0.052 | 0.052 |
| Electricity to Process (Btu) | 5,000 | 3,000 |
| Energy Losses from Process (Btu) | 141,000 | 109,000 |
| Pressure of Hydrogen from Production (psi) | 300 | 300 |
| Energy Use for Delivery Operations at the Forecourt (Btu) | Negligible | 7,200 |
| Energy Use for Delivery Transport (Btu) | 34,000 | 2,000 |
| Hydrogen Dispensing Fill Pressure (psi) | 5,000 | 5,000 |
| Plant Gate Energy Use Including Biomass (Btu) | 257,000 | 225,000 |
| Production Process Efficiency | 45% | 52% |
| Pathway Efficiency | 40% | 49% |
| Greenhouse Gas Emissions from Production (lb/gge of hydrogen produced) | 2.3 | 2.0 |

## Figure B-5. Centralized Hydrogen Production from Coal Gasification with Sequestration

The figure below represents a process for hydrogen production from coal that uses gasification/reforming technology with hot-gas cleanup, a water-gas shift process, and carbon dioxide sequestration. The hydrogen produced is separated at low pressure (~300 psi) and compressed before delivery to the hydrogen distribution system. Oxygen is used so that a concentrated stream of carbon dioxide is produced for sequestration. The petroleum energy use and the $CO_2$ emissions from this process are associated with the inability to sequester all of the $CO_2$ produced in the gasification process, the inefficiency of the sequestration process, and the energy needed for hydrogen liquefaction/pipeline compression, delivery, and compression of the hydrogen at the forecourt.




| Well-to-Wheels Energy and Greenhouse Gas Emissions Data | | | | |
|---|---|---|---|---|
| | Current (2005) Gasoline ICE Vehicle | Current (2005) Gasoline Hybrid Electric Vehicle | Current (2005) Coal with Sequestration - FCV | Future (2030) Coal with Sequestration - FCV |
| Well-to-Wheels Total Energy Use (Btu/mile) | 5,900 | 4,200 | 5,100 | 3,200 |
| Well-to-Wheels Petroleum Energy Use (Btu/mile) | 5,300 | 3,800 | 100 | 40 |
| Well-to-Wheels Greenhouse Gas Emissions ($gCO_2e$/mile) | 470 | 340 | 210 | 60 |
| Cost of Hydrogen ($/gge, Delivered) | | | 5.10 | 2.20 |

*This analysis is based on the best available technology in the laboratory. Currently, it has not been validated through demonstration.*

Notes: Centralized Hydrogen Production from Coal Gasification with Sequestration

1. Source: Well-to-wheels energy, petroleum, and greenhouse gas emissions information from the Argonne National Laboratory GREET model, Version 1.7. Well-to-wheels values represent primary fuel production, electricity production, hydrogen production, and hydrogen delivery. Fossil resource exploration and equipment manufacture are not included.
2. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the current (2005) case are from the National Renewable Energy Laboratory and the H2A model, Version 1.0.9, Central Coal Gasification plant with a capacity of 308,000 kg/day.
3. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values for the future (2030) case are from the Central Coal Gasification H2A model case, Version 1.0.9.

4. Basis is 1 kg of hydrogen, dispensed from filling station for 5,000 psi fills. A kg of hydrogen contains approximately the same amount of energy as one gallon of gasoline, or one gallon of gasoline equivalent (gge).
5. Diagram is for future (2030) case, showing feedstock and energy consumption levels required to meet technology cost goals. Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.
6. The petroleum use and resultant GHG emissions are associated with the grid electricity for delivery, as well as $CO_2$ that could not be captured and sequestered. 85% of the plant $CO_2$ is assumed to be captured and sequestered. $CO_2$ separation and sequestration costs are $15/metric tonne of carbon.
7. Fossil-based power plants generating grid electricity for the future (2030) case are assumed to sequester carbon emissions at a rate of 85%.
8. Production plant electricity requirements for the future (2030) case are met through internally-generated power.
9. The hydrogen delivery in the current (2005) case assumes liquid hydrogen delivery by truck from a central plant located 76 miles from the forecourt station. Liquefier efficiency is 77.4%. Truck fuel consumption is 6 mi/gallon. Data were obtained from the H2A Delivery Scenario Model and GREET. The future (2030) case assumes hydrogen pipeline delivery over 76 miles. Delivery costs include necessary compression and/or liquefaction equipment.
10. Cost of hydrogen delivery for the current (2005) and future (2030) cases is assumed to be $3.50/kg and $1.00/kg, respectively.
11. For the current (2005) case, hydrogen is assumed to be received at the forecourt as a liquid and dispensed as a gas for 5,000 psi fills. For the future (2030) case, hydrogen is assumed to be received at the forecourt as gaseous hydrogen at 250 psi by pipeline and dispensed for 5,000 psi fills. The cost of the forecourt operations is included in the delivery cost.
12. Efficiency results are presented in terms of lower heating value (LHV) of hydrogen.
13. Future (2030) case assumes pipeline compressed gas delivery to the forecourt station. Pipeline energy use calculated using the H2A Delivery Models.
14. The efficiency of the electric forecourt compressor, which raises the pressure of the gaseous hydrogen for 5,000 psi fills, is 94%.
15. The operating capacity factor of the production plant is 90%.
16. Coal feedstock prices are based on the 2015 projections for electric utility steam coal by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Prices shown in table are in 2005 $. Feedstock is inflated at 1.9%/year for the 40-year operating life of the plant.
17. Electricity is consumed by the process for compression and plant operations. Electricity prices are based on the 2015 projections for industrial-rate electricity by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Prices shown in table are in 2005 $. Electricity is inflated at 1.9%/year for the 40-year operating life of the plant.
18. The levelized capital costs for the current (2005) and future (2030) cases are $1.00/kg hydrogen and $0.67/kg of hydrogen, respectively.
19. Cost of hydrogen is the minimum required to obtain a 10% internal rate of return after taxes on the capital investment.
20. The data relevant to the Centralized Hydrogen Production from Coal Gasification with Sequestration technology diagram above are provided in the table below.

| | Current (2005) Coal with Sequestration - FCV | Future (2030) Coal with Sequestration - FCV |
|---|---|---|
| Coal Feedstock Price ($/million Btu LHV) | 1.19 | 1.19 |
| Coal Feedstock Price ($/ton) | 26.70 | 26.70 |
| Energy in Coal Feedstock (Btu) | 194,000 | 189,000 |
| Electricity Price ($/kWh) | 0.052 | N/A-process electricity internally generated |
| Electricity to Process (Btu) | 1,000 | - |
| Energy Losses from Process (Btu) | 79,000 | 73,000 |
| Pressure of Hydrogen from Production (psi) | 300 | 300 |
| Energy Use for Delivery at the Forecourt (Btu) | Negligible | 7,200 |
| Energy Use for Delivery Transport (Btu) | 34,000 | 2,000 |
| Hydrogen Dispensing Fill Pressure (psi) | 5,000 | 5,000 |
| Plant Gate Energy Use Including Coal Feedstock (Btu) | 195,000 | 189,000 |
| Production Process Efficiency | 59% | 61% |
| Pathway Efficiency | 51% | 58% |
| $CO_2$ Sequestered (lb/gge of hydrogen produced) | 38 | 37 |
| Greenhouse Gas Emissions from Production (lb/gge of hydrogen produced) | 7.2 | 7.0 |

## Figure B-6. Centralized Hydrogen Production from Nuclear Sulfur-Iodine Process

The figure below represents a process for hydrogen production from nuclear energy that utilizes the sulfur-iodine thermochemical water splitting process. In this configuration, the high temperature heat from the advanced nuclear reactors is used as the energy source for the sulfur-iodine thermochemical process to produce hydrogen from water. The produced hydrogen is scrubbed of impurities at low pressure and is compressed to deliver the hydrogen to the distribution system. The petroleum energy use and $CO_2$ emissions from this process are associated with the electricity needed to operate the process as well as the energy needed for hydrogen delivery. Only a future case is shown because this technology is in a relatively early stage of development.

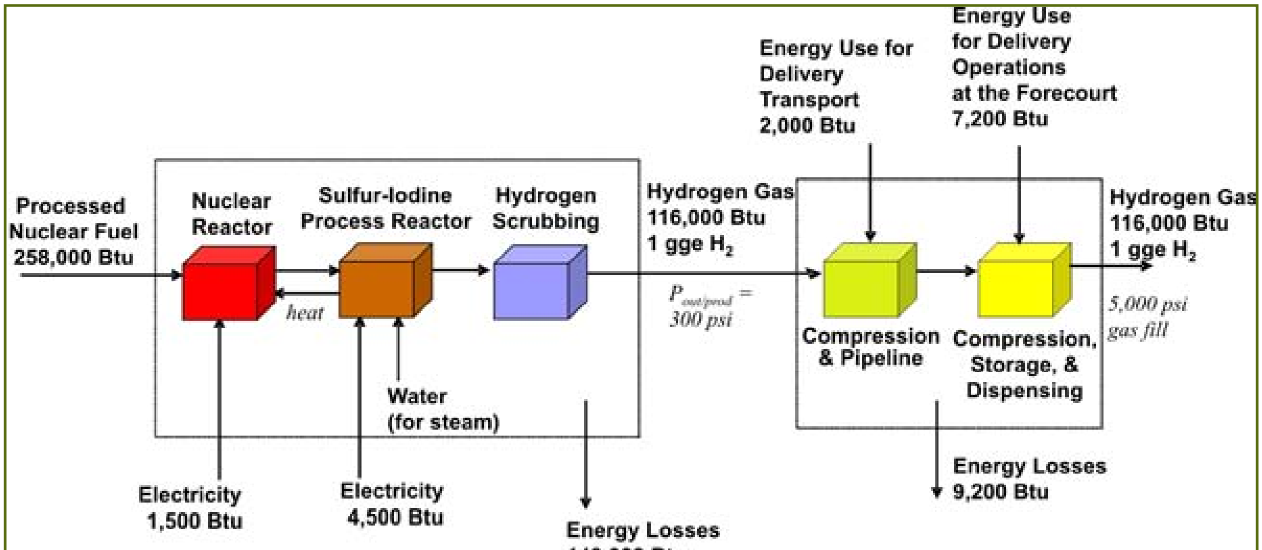



Figure Represents Future (2030) Case.

Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.

| Well-to-Wheels Energy and Greenhouse Gas Emissions Data | | | |
|---|---|---|---|
| | Current (2005) Gasoline ICE Vehicle | Current (2005) Gasoline Hybrid Electric Vehicle | Future (2030) Nuclear Sulfur Iodine - FCV |
| Well-to-Wheels Total Energy Use (Btu/mile) | 5,900 | 4,200 | 4,700 |
| Well-to-Wheels Petroleum Energy Use (Btu/mile) | 5,300 | 3,800 | 40 |
| Well-to-Wheels Greenhouse Gas Emissions ($gCO_2e$/mile) | 470 | 340 | 60 |
| Cost of Hydrogen ($/gge, Delivered) | | | 3.20 |

*This analysis is based on the best available technology in the laboratory. Currently, it has not been validated through demonstration.*

Notes: Centralized Hydrogen Production from Nuclear Sulfur-Iodine Process

1. Source: Well-to-wheels energy, petroleum, and greenhouse gas emissions information from the Argonne National Laboratory GREET model, Version 1.7. Well-to-wheels values represent primary fuel production, electricity production, hydrogen production, and hydrogen delivery. Fossil resource exploration and equipment manufacture are not included.
2. Source: Cost, resource requirements, energy requirements, all fuel and feedstock energy contents, and efficiency values from the National Renewable Energy Laboratory and the H2A model, Version 1.0.9 for a Central Nuclear Sulfur-Iodine Thermo-chemical plant with the capacity of 768,000 kg/day.
3. Basis is 1 kg of hydrogen, dispensed from filling station for 5,000 psi fills. A kg of hydrogen contains approximately the same amount of energy as one gallon of gasoline, or one gallon of gasoline equivalent (gge).
4. Diagram is for future (2030) case. Flows in diagram represent direct energy and emissions between production and dispensing, and are not based on well-to-wheels calculations.
5. The petroleum use and resultant GHG emissions are associated with the grid electricity for the production process and hydrogen delivery.

6. Cost of hydrogen delivery is assumed to be \$1.00/kg. Hydrogen is assumed to be received at the forecourt as gaseous hydrogen at 250 psi by pipeline and dispensed for 5,000 psi fills. The cost of the forecourt operations is included in the delivery cost.

7. Efficiency results are presented in terms of lower heating value (LHV) of hydrogen.
8. Nuclear Fuel Cycle Cost of \$9.3/MWh - based on U3O8 @ \$38/lb, enriched @ \$55/SWU (separative work unit). SWU and uranium prices are the levelized prices over 40 years assuming a 10% discount rate and a 10.2% capital recovery factor applied to data from EIA and extrapolated in the PNNL Mini-Cam model. See www.eia.doe.gov/cneaf/nuclear/page/forecast/projection.html for more information.
9. Future (2030) case assumes pipeline compressed gas delivery to the forecourt station. Pipeline energy use calculated using the H2A Delivery Models.
10. The efficiency of the electric forecourt compressor, which raises the pressure of the gaseous hydrogen for 5,000 psi fills, is 94%.
11. The operating capacity factor of the production plant is 90%.
12. Electricity is consumed by the process for compression and plant operations. Electricity price is based on the 2015 projection for industrial-rate electricity by the DOE Energy Information Administration *Annual Energy Outlook 2005* High A case. Price shown in the table is in 2005 \$. Electricity is inflated at 1.9%/year for the 40-year operating life of the plant.
13. The levelized capital cost \$1.30/kg hydrogen.

| | Future (2030) Nuclear Sulfur Iodine - FCV |
|---|---|
| **Nuclear Cycle Feedstock Price** | See note #8 |
| **Energy in Feedstock (Btu)** | 258,000 |
| **Electricity Price (\$/kWh)** | 0.052 |
| **Energy Losses from Process (Btu)** | 148,000 |
| **Pressure of Hydrogen from Production (psi)** | 300 |
| **Energy Use for Delivery at the Forecourt (Btu)** | 7,200 |
| **Energy Use for Delivery Transport (Btu)** | 2,000 |
| **Pressure of Hydrogen from Dispenser (psi)** | 5,000 |
| **Plant Gate Energy Use Including Feedstock (Btu)** | 264,000 |
| **Production Process Efficiency** | 44% |
| **Pathway Efficiency** | 42% |

# Appendix C. Hydrogen Fuel Initiative Budget: FY 04-FY 07[1]

| | FY 2004 Appropriation[2] ($000) | FY 2005 Appropriation[3] ($000) | FY 2006 Appropriation[4] ($000) | FY 2007 Request[5] ($000) |
|---|---|---|---|---|
| Basic Research | $0 | $29,183 | $32,500 | $50,000 |
| Production and Delivery | $19,163 | $31,503 | $48,534 | $79,120 |
| Storage | $13,628 | $22,418 | $26,040 | $34,620 |
| Conversion (Fuel Cells) | $53,954 | $55,759 | $33,336 | $57,075 |
| Technology Validation | $15,648 | $26,098 | $33,301 | $39,566 |
| Manufacturing R&D | $0 | $0 | $0 | $1,978 |
| Safety, Codes and Standards[6] | $6,310 | $6,350 | $6,006 | $15,268 |
| Education | $2,417 | $0 | $481 | $1,978 |
| Systems Analysis | $1,429 | $3,157 | $4,787 | $9,892 |
| Congressionally Directed Funds | $43,967 | $47,236 | $47,470 | $0 |
| TOTAL | $156,516 | $221,704 | $232,455 | $289,497 |

1 U.S. Department of Energy (Hydrogen Program), "Record 5010: HFI Budget FY 2004-2007," http://www.hydrogen.energy.gov/program_records.html.

2 U.S. House, 108th Congress, 1st Session, H.R. 2754, *Energy and Water Development Appropriations Act, 2004* (Public Law 108-137), retrieved February 3, 2006, from http://thomas.loc.gov; U.S. House, 108th Congress, 1st Session, H.R. 2691, *Department of the Interior and Related Agencies Appropriations Act, 2004* (Public Law 108-108), retrieved February 3, 2006, from http://thomas.loc.gov; U.S. House, 108th Congress, 1st Session, H.R. 2673, *Consolidated Appropriations Act, 2004* (Public Law 108-199), retrieved April 6, 2006, from http://thomas.loc.gov. Numbers include a 2.8% reduction of the R&D budget, to be used for SBIR/STRR. This funding is managed separately, but remains focused on hydrogen activities consistent with the original appropriation.

3 U.S. House, 108th Congress, 2nd Session, H.R. 4614, Committee Approval Report Making Appropriations for Energy and Water Development for the Fiscal Year Ending September 30, 2005, and for Other Purposes, http://thomas.loc.gov; U.S. House, 108th Congress, 2nd Session, H.R. 4568, Committee Approval Report Making Appropriations for the Department of the Interior and Related Agencies for the Fiscal Year Ending September 30, 2005, and for Other Purposes, http://thomas.loc.gov; U.S. House, 108th Congress, 2nd Session, H.R. 4818, *Consolidated Appropriations Act, 2005* (Public Law 108-447), retrieved April 6, 2006, from http://thomas.loc.gov; U.S. House, 109th Congress, 1st Session, House Report 1268, *Emergency Supplemental Appropriations Act for Defense, the Global War on Terror, and Tsunami Relief, 2005* (Public Law 109-13), retrieved April 6, 2006, from http://thomas.loc.gov. Numbers include a 2.8% reduction of the R&D budget, to be used for SBIR/STRR. This funding is managed separately, but remains focused on hydrogen activities consistent with the original appropriation.

4 U.S. House, 109th Congress, 1st Session, H.R. 2419, *Energy and Water Development Appropriations Act, 2006* (Public Law 109-103), retrieved April 6, 2006, from http://thomas.loc.gov. Numbers include a 2.8% reduction of the R&D budget, to be used for SBIR/STRR. This funding is managed separately, but remains focused on hydrogen activities consistent with the original appropriation.

5 U.S. DOE, Office of Management, Budget and Evaluation, http://www.mbe.doe.gov/budget.

6 Includes funding for Department of Transportation.

# Appendix D. Glossary/Acronyms

| | |
|---|---|
| Btu | British thermal unit |
| CFO | DOE Office of the Chief Financial Officer |
| $CO_2$ | Carbon dioxide |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| EE | DOE Office of Energy Efficiency and Renewable Energy |
| EIA | Energy Information Administration |
| FCV | Fuel cell vehicle |
| FE | DOE Office of Fossil Energy |
| FY | Fiscal year |
| gge | Gallons of gasoline equivalent |
| $gCO_2e$ | Grams of carbon dioxide equivalent |
| GHG | Greenhouse gas |
| GPRA | Government Performance and Results Act |
| GWe | Gigawatt-Electric |
| GWth | Gigawatt-Thermal |
| HTAC | Hydrogen and Fuel Cell Technical Advisory Committee |
| ICE | Internal combustion engine |
| ILC | Implementation Liaison Committee (IPHE) |
| IPHE | International Partnership for the Hydrogen Economy |
| JPY | Japanese yen |
| kg | Kilogram |
| $kgCO_2e$ | Kilograms of carbon dioxide equivalent |
| kW | Kilowatt |
| kWh | Kilowatt hour |
| l | Liter |
| lb | Pound |
| LDV | Light-duty vehicle |
| LHV | Lower heating value |
| m | Meter |
| mbpd | Million barrels per day |
| METI | Ministry of Economy, Trade, and Industry (Japan) |
| MMT | Million metric tons |
| MMTCE | Million metric tons of carbon equivalent |
| NAS | National Academy of Sciences |
| NE | DOE Office of Nuclear Energy |
| NEP | National Energy Policy |
| NHI | Nuclear Hydrogen Initiative |
| NOx | Nitrogen oxides |
| NRC | National Research Council |
| NSF | National Science Foundation |
| PEM | Polymer electrolyte membrane |
| PI | DOE Office of Policy and International Affairs |
| PSA | Pressure swing absorption |
| psi | Pounds per square inch |
| psig | Pounds per square inch gauge |
| R&D | Research and development |

| | |
|---|---|
| RD&D | Research, development, and demonstration |
| SC | DOE Office of Science |
| SECA | Solid State Energy Conversion Alliance |
| SMR | Steam methane reformer |
| SOFC | Solid oxide fuel cell |
| SOx | Sulfur oxide |
| V | Volt |
| VHTR | Very high temperature reactor |
| VOC | Volatile organic compound |
| W | Watt |
| wt | Weight |
| WTW | Well-to-wheels |

# Appendix E. Contacts, Resources, and Weblinks

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## Document Citations

The DOE Hydrogen Program draws guidance and direction from a number of different policy and program planning instruments, as shown in Figure E-1. Citations for these documents are provided below.

*National Energy Policy*
May 2001
www.whitehouse.gov/energy

*Energy Policy Act of 2005*
http://thomas.loc.gov

*The Department of Energy Strategic Plan: Protecting National, Energy, and Economic Security with Advanced Science and Technology and Ensuring Environmental Cleanup*
September 2003
http://strategicplan.doe.gov/full.pdf

*Office of Energy Efficiency and Renewable Energy Strategic Plan*
October 2002
http://www1.eere.energy.gov/office_eere/pdfs/fy02_strategic_plan.pdf

*A National Vision of America's Transition to a Hydrogen Economy: To 2030 and Beyond*
February 2002
www.hydrogen.energy.gov

*National Hydrogen Energy Roadmap*
November 2002
www.hydrogen.energy.gov

Figure E-1. Hydrogen Fuel Initiative: Policy and RD&D Planning Documents


*Fuel Cell Report to Congress*
February 2003
http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf

*Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan* (Office of Energy Efficiency & Renewable Energy)
February 2005
www.eere.energy.gov/hydrogenandfuelcells/mypp/

*Hydrogen from Coal Program Research, Development, and Demonstration Plan* (Office of Fossil Energy)
June 2004 (Draft)
www.fe.doe.gov/programs/fuels/publications/programplans/2004/hydrogen_external_061004.pdf

*Nuclear Hydrogen R&D Plan* (Office of Nuclear Energy, Science & Technology)
March 2004
www.hydrogen.energy.gov/pdfs/nuclear_energy_h2_plan.pdf

*Basic Research Needs for the Hydrogen Economy* (Office of Science)
May 2003
www.sc.doe.gov/bes/hydrogen.pdf

*Department of Energy FY 2006 Budget Request*
www.mbe.doe.gov/budget/06budget/start.htm

*FY2006 Energy and Water Appropriation*
http://thomas.loc.gov

## *Web Sites of Relevant Organizations*

Office of Science and Technology Policy, Interagency Hydrogen and Fuel Cell Technical Task Force
www.hydrogen.gov

DOE Hydrogen Program
www.hydrogen.energy.gov

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

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

FreedomCAR and Vehicle Technologies Program
www.eere.energy.gov/vehiclesandfuels

Office of Fossil Energy
www.fe.doe.gov

Office of Nuclear Energy
www.nuclear.gov

Office of Science
www.science.doe.gov

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

Department of Transportation
www.dot.gov