

# **One Giant Leap: A U.S. Hydrogen Policy**

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## Introduction

This paper draws on hydrogen policy literature and U.S. government policy to offer a vision of hydrogen as our nation's premiere energy source used for transportation, in buildings and homes, and for portable devices such as cell phones and laptops. That vision is contrasted with the state of the art today to show the ground that needs to be covered to bring this to fruition. Several ways to cross that ground are discussed and broad recommendations are presented to guide the development of a hydrogen plank for the presidential campaign and shape the energy policy of the new administration.

Hydrogen is the next great source of global energy. From wood to coal to oil, we now move to hydrogen as a zero emission, limitless energy source. This is compelled by pressing issues of climate change, dwindling fossil fuel supplies, growing air pollution, and national security. Between where we are and where we need to be there is some challenging terrain to be crossed, but there are clear transitional strategies available and the goal is well in sight. Those who make this journey will claim the prize of abundant clean energy in a world where energy is king.

What is most in question is how to get there and who will get there first. Like the "space race" between the U.S. and the Soviet Union in the 1950s and 1960s, hydrogen supremacy will confer much more on the winner than victory. The U.S. space program distributed new technologies that truly ushered in the "space age." Military applications strengthened our defense. Our position as the world's most advanced nation was secured. We experienced as a people the daring of conjuring an audacious vision, then bringing it into reality. Hydrogen supremacy promises all of this and more.

The U.S. hydrogen policy proposed in this paper (see page 19) urges a tightly coordinated and integrated Apollo-scale program to rapidly cover the remaining ground to the hydrogen economy. This approach involves substantial leadership by the new president and the federal government, complimented by private industry. Sustained public education to build broad popular support is also paramount. This kind of leadership has given our nation its highways, major dams and bridges, national parks, rural power grid and other shared resources. Such projects are worthy of the considerable governmental investment and national commitment they require.

An action plan for reaching the hydrogen economy is already being implemented in India. Smaller nations like Iceland are also taking bold steps. The U.S. must accelerate its own efforts now to secure a lead position in the vital pursuit of this prime energy prize.

Comments or questions about this policy paper can be directed to Tom Sheehan ([tsheehan@hythane.com](mailto:tsheehan@hythane.com)). We hope this will help in your important work as you fashion a new direction for our nation.

## I. Why Hydrogen

Every energy source in history has one thing in common: each contains hydrogen. The first element in the Periodic Table, it is the lightest and most abundant element in the universe. A colorless, odorless gas, hydrogen is found in water and all organic compounds.

Hydrogen has been explored as a transportation energy source for decades in the U.S., first gaining official interest during the 1973 oil crisis. As petroleum prices came down, the urgency receded but has now returned to the forefront due to economic, environmental, and security reasons. Interest centers on hydrogen for use as an energy source for vehicles, commercial buildings and residences, and personal devices and appliances.

### Policy Drivers

In a review of 40 hydrogen policy and envisioning studies published between 1996 and 2004 (McDowall, Eames, 2006)<sup>1</sup>, four issues emerge as the central policy drivers:

*Climate change:* Reducing carbon dioxide emissions is considered most important, with climate change cited by all of the studies. Hydrogen is viewed as facilitating “the transition from limited nonrenewable stocks of fossil fuels to unlimited flows of renewable sources, playing an essential role in the ‘decarbonization’ of the global energy system needed to avoid the most severe effects of climate change. (Dunn, S., 2001)<sup>2</sup>

*Energy security:* This includes concerns about finite oil and gas reserves, their geopolitical sensitivity and location, energy prices, and the vulnerability of centralized energy systems to attack. “By providing a secure and abundant domestic supply of fuel, hydrogen would significantly reduce oil import requirements, providing the energy independence and security that many nations crave.” (Schwartz, Randall, 2003)

*Local Air quality:* Reduction in local air pollution is seen as a significant benefit of hydrogen. “Hydrogen has the potential for replacing essentially all gasoline and eliminating almost all CO<sub>2</sub> from vehicular emissions.” (National Research Council, National Academy of Engineering, 2004)<sup>3</sup> “By enabling the spread of appliances, more decentralized ‘micropower’ plants, and vehicles based on efficient fuel cells, whose only byproduct is water, hydrogen would dramatically cut emissions of particulates, carbon monoxide, sulfur and nitrogen oxides, and other local air pollutants.” (Schwartz, Randall, 2003)

*Competitiveness:* Several studies refer to international competitiveness. Sometimes overlooked, we view this issue as paramount from a national policy perspective. Dunn (2001) develops this in detail:

“Coal fueled the eighteenth- and nineteenth-century rise of Great Britain and modern Germany; in the twentieth century, oil laid the foundation for the United

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<sup>1</sup> pp. 1237, 1242-1243

<sup>2</sup> pp. 9

<sup>3</sup> pp.1

States' unprecedented economic and military power. Today's U.S. superpower status, in turn, may eventually be eclipsed by countries that harness hydrogen as aggressively as the United States tapped oil a century ago. Countries that focus their efforts on producing oil until the resource is gone will be left behind...As Don Huberts, CEO of Shell Hydrogen, has noted: 'The Stone Age did not end because we ran out of stones, and the oil age will not end because we run out of oil.'

"In time, U.S. fuel cell and hydrogen-extraction technology will provide enormous opportunities for developing nations like China and India, which will be the fastest-growing consumers of energy in coming decades. Because they don't have an adequate petroleum-based infrastructure today, these nations will be quick to take full advantage of hydrogen, leapfrogging developed countries."<sup>4</sup>

### Applications

For transportation, hydrogen can be used in a fuel cell or burned in a combustion engine. When burned in an engine, Hydrogen is about 30% percent more efficient than gasoline and does not emit carbon dioxide.

In a fuel cell, hydrogen acts as an energy carrier, proving to be 100% to 200% more efficient than gasoline, with clean water as the only byproduct. From well-to-tank, hydrogen fuel cell vehicles (FCV) present a near-zero Greenhouse Gas (GHG) transportation pathway when produced from renewable energy. From tank-to-wheels, FCVs produce no GHGs, only water vapor as exhaust. Renewable hydrogen is seen as sufficient to provide for long-term U.S. transportation needs. (Arvizu, 2008)

For commercial buildings, stationary hydrogen fuel cells are already in use at hospitals, police stations, banks, and wastewater treatment plants to provide electricity, heat, and cooling. On-site hydrogen production is seen as a strategy to lower distribution and infrastructure costs. Personal-use applications involve small fuel cells now being developed for mobile phones, laptop computers, portable electronics, and household appliances.

"A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by-product. As long as fuel is supplied, the fuel cell will continue to generate power. Since the conversion of the fuel to energy takes place via an electrochemical process, not combustion, the process is clean, quiet and highly efficient – two to three times more efficient than fuel burning. In addition to low or zero emissions, benefits include high efficiency and reliability, multi-fuel capability, siting flexibility, durability, scalability and ease of maintenance. Fuel cells operate silently, so they reduce noise pollution as well as air pollution and the waste heat from a fuel cell can be used to provide hot water or space heating for a home or office." (Fuel Cells 2000; accessed May 2008, <http://www.fuelcells.org>)

Some nations are moving aggressively to what is called a "hydrogen economy." This term encompasses a society in which clean hydrogen is the predominant and ubiquitous source of power for all applications from industrial to personal. It is both centralized for economies of scale and decentralized for ease of delivery and cost of distribution. The reality of a hydrogen economy is materializing rapidly.

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<sup>4</sup> pp. 9

- In response to severe air pollution, India has charted a path to a hydrogen economy, including having at least 20% of all vehicles using hydrogen-based fuel by 2020 (more than 1 million vehicles). India is embarking on that pathway by converting its 500,000 urban public buses to run on Hythane®, an optimal mix of hydrogen and natural gas that dramatically decreases harmful smog emissions.
- Iceland has committed to become the world's first hydrogen economy by weaning itself from petroleum, which it must import entirely. Like India, the nation is starting with its public bus fleet, fueling it with hydrogen electrolyzed from its abundant natural water resources. With vast geothermal supplies from underground magma, Iceland sees the day when it will fuel all of its vehicles and ships with hydrogen and export hydrogen energy to other countries.
- This year, three major automakers (Honda, BMW, GM) introduced hydrogen cars. These models and others are expected to be commonly seen in showrooms by 2012. Scientists and industry analysts predict that fuel cell and other hybrid vehicles will comprise at least 25% of the U.S. fleet by 2027. Many believe it will happen sooner.
- In a response to air quality concerns, San Francisco International Airport is converting its shuttle bus fleet to run on Hythane® to decrease harmful emissions.
- With the introduction of a new natural gas garbage truck in April 2008, 38 New York City public vehicles are operating on HCNG (hydrogen and natural gas), with more coming on line. Syracuse, NY is also converting its natural gas trucks to Hythane®. Other U.S. cities are waiting for funding to duplicate this model.
- Hydrogen and Hythane® powered vehicles are operating in public and private sector demonstration projects in many U.S. cities and internationally. In the U.S., 38 states have active hydrogen initiatives. California presents the most developed model (<http://www.hydrogenhighway.ca.gov>) in which vehicles and a fueling infrastructure is jointly evolving.

Hydrogen is understood by scientists and advocates worldwide to be the inevitable next step in global energy evolution in which we move from bulky, inefficient, and polluting sources toward clean, renewable energy:

“From wood to coal to oil to natural gas, the ratio of hydrogen (H) to carbon (C) in the molecule of each successive source has increased. Roughly speaking, the ratio is between 1 to 3 and 1 to 10 for wood; 1 to 2 for coal; 2 to 1 for oil; and 4 to 1 for natural gas. Between 1860 and 1990, the H-C ratio rose sixfold. Jesse Ausubel of Rockefeller University argues that ‘the most important, surprising, and happy fact to emerge from energy studies is that for the last 200 years, the world has progressively favored hydrogen atoms over carbon...The trend toward ‘decarbonization’ is at the heart of understanding the evolution of the energy system.’ The next logical fuel in this progression is hydrogen, the lightest and most abundant element in the universe and the power source of our sun.” (Dunn, 2001)<sup>5</sup>

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<sup>5</sup> pp. 13-16

## II. The Hydrogen Vision

*Vision for the Hydrogen Economy:* Hydrogen is America's clean energy choice. Hydrogen is flexible, affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country. (U.S. Department of Energy, 2002)<sup>6</sup>

The path to fundamental change is often preceded by a vision. Perhaps the most prescient hydrogen vision was offered by French author Jules Verne in 1874 when his character Cyrus Smith declares in *The Mysterious Island*: "I believe that water will one day be used as fuel, that the hydrogen and oxygen of which it is constituted will be used, simultaneously or in isolation, to furnish an inexhaustible source of heat and light, more powerful than coal can ever be."<sup>7</sup>

### A Global Hydrogen Vision

The Intergovernmental Panel on Climate Change (IPCC) spurred some modern day hydrogen visioning when it posited 40 models of possible near-term worlds to enable forward-looking climate policy discussions. These were later gathered into four categories, from which one model world emerged as a popular platform for hydrogen visioning. The so-called B1 World is characterized by:

- Rapid economic growth along with rapid changes towards a service and information economy.
- Population rising to 9 billion in 2050, then declining.
- Reductions in material intensity and the introduction of clean and resource-efficient technologies.
- An emphasis on global solutions to economic, social, and environmental stability. (IPCC, 2000)

In such a world:

"The global hydrogen production system, initially fossil-based, progressively shifts towards renewable sources. Fuel cells and other hydrogen-using technologies play a major role in a substantial transformation towards a more flexible, less vulnerable, distributed energy system which meets energy needs in a cleaner, more efficient and cost-effective way. This profound structural transformation of the global energy system brings substantial improvements in energy intensity and an accelerated decarbonization of the energy mix, resulting in relatively low climate impacts. Fossil fuels still dominate the primary energy supply...but during this period, the system shifts away from coal and oil, which reduce their shares substantially, towards natural gas. In turn, natural gas operates as the main transitional fuel to the post-fossil era...Renewable energy sources, in particular biomass, increase their shares substantially. A transition to a decentralized energy system takes place." (Barreto, Makihira, Riahi, 2002)<sup>8</sup>

It is practicable for U.S. energy policy to place itself within this feasible global future. The global shift from wood to coal to oil to natural gas to hydrogen seems organic. The exact placement of nuclear power in this progression is not as widely agreed on but

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<sup>6</sup> p. 2

<sup>7</sup> Jules Verne, *The Mysterious Island*, Random House, 2002, translated by Jordan Stump, p. 327.

<sup>8</sup> pp. 1-2

most policymakers see it reemerging as an important renewable energy source that poses less threat of accident but a significant problem of waste disposal. Certainly, France has placed a long-term bet on nuclear power and may find itself positioned for hydrogen as a result. The use of nuclear power in U.S. energy policy is continually referenced as a practical, cost efficient method of hydrogen production but it remains peripheral due to nuclear power's controversial domestic history. It is time to revisit this in light of a hydrogen economy.

### A U.S. Hydrogen Vision

The U.S. government formally launched a hydrogen vision in 2002 and has been building on it since. Initiated by DOE, the increasing integration of U.S. hydrogen policy now includes coordination with DOT and several other federal agencies. The elements of a U.S. hydrogen energy infrastructure are envisioned as:

#### **Production**

- Production of hydrogen from fossil, nuclear, and renewable resources.
- Thermal, electrolytic, and photolytic processes.

#### **Delivery**

- Distribution of hydrogen from production and storage sites.
- Use of pipelines, trucks, rail, and barges.
- Efficient reversible solid or liquid carrier systems.

#### **Storage**

- Containment of hydrogen for delivery, conversion, and use.
- Tanks for compressed gases and liquids.
- Reversible and regenerable solid- and liquid-state systems, including metal and chemical hydrides.

#### **Conversion**

- Use of hydrogen to generate electricity and/or thermal energy.
- Combustion turbines, reciprocating engines, and fuel cells.

#### **Applications**

- Use of hydrogen for stationary energy generation systems, including distributed energy systems, central generating stations, and combined heat and power applications.
- Performance and safety evaluations and development of codes/standards. (U.S. Department of Energy and U.S. Department of Transportation, 2006)

Within each of these areas, there is also a vision in place of where the nation should be headed:

**Production:** Hydrogen will become a premier energy carrier, reducing U.S. dependence on imported petroleum, diversifying energy sources, and reducing pollution and greenhouse gas emissions. It will be produced in large refineries in industrial areas, power parks and fueling stations in communities, distributed facilities in rural areas and on-site at customers' premises. Thermal, electric, and photolytic processes will use fossil fuels, biomass, or water as feedstocks and release little or no carbon dioxide into the atmosphere.

**Delivery:** A national supply network will evolve from the existing fossil fuel-based infrastructure to accommodate both centralized and decentralized production facilities. Pipelines will distribute hydrogen to high-demand areas, and trucks and rail will distribute

hydrogen to rural and other lower-demand areas. On-site hydrogen production and distribution facilities will be built where demand is high enough to sustain maintenance of the technologies.

**Storage:** A selection of relatively lightweight, low-cost, and low-volume hydrogen storage devices will be available to meet a variety of energy needs. Pocket-sized containers will provide hydrogen for portable telecommunications and computer equipment, small and medium hydrogen containers will be available for vehicles and on-site power systems, and industrial-sized storage devices will be available for power parks and utility-scale systems. Solid-state storage media that use metal hydrides will be in mass production as a mature technology. Storage devices based on carbon structures will be developed.

**Conversion:** Fuel cells will be a mature, cost-competitive technology in mass production. Advanced, hydrogen-powered energy generation devices such as combustion turbines and reciprocating engines will enjoy widespread commercial use.

**Applications:** Hydrogen will be available for every end-use energy need in the economy, including transportation, power generation, industrial process heaters, and portable power systems. Hydrogen will be the dominant fuel for government and commercial vehicle fleets. It will be used in a large share of personal vehicles and light duty trucks. It will be combusted directly and mixed with natural gas in turbines and reciprocating engines to generate electricity and thermal energy for homes, offices and factories. It will be used in fuel cells for both mobile and stationary applications. And it will be used in portable devices such as computers, mobile phones, Internet hook-ups, and other electronic equipment. (U.S. Department of Energy, 2002)<sup>9</sup>

An estimated 40 million tons of hydrogen per year would fuel 100 million fuel-cell powered cars or provide electricity to 25 million residences. One scenario to reach this volume involves both centralized and decentralized production using a variety of technologies, creating a variegated picture of the U.S. hydrogen economy:

- 100,000 neighborhood electrolyzers 4 million tons
- 15,000 small reformers in refueling stations 8 million tons
- 30 coal/biomass gasification plants 8 million tons
- 10 nuclear water splitting plants 4 million tons
- 7 large oil and gas SMR/gasification refineries 16 million tons (U.S. Department of Energy, 2002).<sup>10</sup>

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<sup>9</sup> pp. 8, 13, 18, 24. 30

<sup>10</sup> p. 11

### III. Hydrogen Today

Although hydrogen is the most abundant element in the universe, it combines easily with other elements and does not naturally exist in its elemental form on Earth. It must be extracted from other compounds such as fossil fuels, biomass, or water, requiring the use of thermal (heat), electrolytic (electricity), or photolytic (light) energy. Hydrogen can be distributed by pipelines, trucks, or other means, or stored as a liquid, gas, or chemical compound. It is converted into energy by fuel cells or by combustion in turbines and engines.

About nine million tons of hydrogen is produced in the U.S. annually, enough to power 20 to 30 million hydrogen cars or 5 to 8 million homes.<sup>11</sup> Major industrial uses of hydrogen include making ammonia for fertilizer, removing sulfur from gasoline, chemical processing, and production of methanol and refined metals. It is also used in the production of vitamins, cosmetics, semiconductor circuits, soaps, lubricants, cleaners, and even margarine and peanut butter. It is perhaps best known for its use as rocket fuel.

Tracking the same elements used to structure the hydrogen vision provides a profile of hydrogen today:

**Production:** Hydrogen is produced in a limited number of plants. Steam methane reforming accounts for 95% of U.S. hydrogen production. Other production methods are partial oxidation of fossil fuels in large gasifiers and using electricity in electrolyzers to extract hydrogen from water.<sup>12</sup>

**Delivery:** Hydrogen is currently transported by pipeline or by roads using cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail car or barge.<sup>13</sup>

**Storage:** Hydrogen can be stored as a discrete gas or liquid or in a chemical compound. The storage of compressed hydrogen gas in tanks is the most mature technology. Chemical hydrides are emerging as an alternative to direct hydrogen storage that is inherently safer than storage of volatile and flammable fuel, be it hydrogen, gasoline, or methanol.<sup>14</sup>

**Conversion:** The use of hydrogen in engines is fairly well developed (i.e. NASA, DOD). Other combustion applications are under development, including new combustion equipment for hydrogen in turbines and engine. Fuel cells are in various stages of development.<sup>15</sup>

**Applications:** Transportation applications include buses, trucks, passenger vehicles, and trains. BMW, Honda, and General Motors are rolling out their first commercial vehicles this year: BMW's Hydrogen 7 burns hydrogen as fuel; Honda's FCX Clarity is a fuel cell vehicle, as are Chevrolet's Sequel and Equinox models. Stationary power applications include back-up power units, grid management, power for remote locations,

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<sup>11</sup> U.S. Department of Energy, 2002, p. 7

<sup>12</sup> Ibid, p. 7

<sup>13</sup> Ibid, p. 13

<sup>14</sup> Ibid, p. 17

<sup>15</sup> Ibid, p. 23

stand-alone power plants for towns and cities, distributed generation for buildings, and cogeneration in which excess thermal energy from electricity generation is used for heat.<sup>16</sup> Portable applications for fuel cells include consumer electronics, business machinery, and recreational devices.<sup>17</sup>

### Federal Program Integration

U.S. government DOE and DOT hydrogen initiatives are being consolidated under the Hydrogen Program with the central mission to research, develop, and validate technologies for hydrogen production, delivery, storage and fuel cell technologies, and using hydrogen in an efficient, clean, safe, reliable, and affordable manner. (U.S. Department of Energy and U.S. Department of Transportation, 2006)<sup>18</sup> A 2007 report by the Hydrogen Program<sup>19</sup> cites progress in overcoming some “critical path” challenges:

- Cost of polymer electrolyte membrane fuel cell systems has been reduced to \$100/kW.
- Cost of distributed hydrogen production from natural gas has been reduced to \$3.00 per gallon of gas equivalent (gge).
- New materials with potential for high hydrogen storage capacity have been identified and are under development.
- Learning demonstrations have provided valuable data on performance of fuel cell vehicles and hydrogen stations in real world applications.<sup>20</sup>

The Interagency Hydrogen and Fuel Cell Technical Task Force, created by the Energy Policy Act of 2005, has been established to coordinate the hydrogen efforts of the Office of Science and Technology Policy; the Departments of Energy, Transportation, Defense, Commerce, and Agriculture; the Office of Management and Budget; the National Science Foundation; the Environmental Protection Agency; the National Aeronautics and Space Administration; and other agencies as appropriate. Its work is ongoing.

Related federal programs that contribute to resolving technical barriers to hydrogen energy use include the 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. The DOE continues with development of advanced hybrid components and electric powertrain technologies for use in hybrid and fuel cell vehicles.<sup>21</sup>

### Today’s Challenges

McDowall and Eames’ review of 40 hydrogen policy and visioning studies indicates three prominent challenges facing the hydrogen economy:

- Absence of a hydrogen refueling infrastructure: the difficulty of establishing a market for FCVs in the absence of a refueling infrastructure—and vice versa (i.e. “chicken & egg” dilemma).
- High costs: particularly of fuel cells and low-carbon hydrogen production.

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<sup>16</sup> U.S. Department of Energy, 2002, p. 29

<sup>17</sup> Ibid, pp. 29-30

<sup>18</sup> p.13

<sup>19</sup> U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2007

<sup>20</sup> Ibid, p. ES-3

<sup>21</sup> Ibid, p. iv

- Technological immaturity: hydrogen on-board storage, consequently limited current driving range of hydrogen vehicles; limited life-time of cells.

Other frequently cited barriers include safety, public acceptability, and the absence of codes and standards. (McDowall, Eames, 2006)<sup>22</sup>

The National Renewable Energy Laboratory (Arvizu, 2008) echoes these concerns, noting that the primary barrier to hydrogen as an energy source is cost, and that “some of the pathways are getting close to competitive, game-changing technologies need continued R&D.”

According to a report by the National Research Council and the National Academy of Engineering (2004), “The four fundamental technological and technical challenges are: to develop and introduce economic, durable, safe, and environmentally acceptable fuel cells and hydrogen storage systems; to develop the infrastructure to provide hydrogen for the light duty vehicle user; to reduce sharply the costs of hydrogen production from renewable over the next few decades.”<sup>23</sup>

Honing in on the issue of public acceptability, DOE concludes;

- The public lacks awareness. Consumers are generally unaware of hydrogen as an energy alternative.
- A lack of structured education programs on hydrogen exists at all levels. Teacher training on the benefits of hydrogen has not been a priority, and students are not being introduced to hydrogen.
- Policies are inconsistent. Policy makers often are not knowledgeable about hydrogen as a fuel, nor do they understand how it works.
- Consumers may unnecessarily fear hydrogen if they are misinformed about its safety, and may hold misconceptions about the risk of using it in homes, businesses, and automobiles. (U.S. Department of Energy, 2002)<sup>24</sup>

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<sup>22</sup> p. 1243

<sup>23</sup> pp. 1,2

<sup>24</sup> pp. 35-36

#### IV. Transitioning to Hydrogen

There are conflicting views on how and how long it will take to make the transition to a hydrogen economy. Some believe we are already well into an inevitable process that will show fruit by 2015 or earlier; others project timelines of 20 to 40 years.

In their review of hydrogen policy and visioning studies, McDowall and Eames (2006) note two possible hydrogen architectures that have transition implication:

- *Decentralized architectures*: Based on local production of hydrogen from electrolysis, biomass processes, or steam reforming of natural gas, hydrogen production is from local energy sources. Decentralized hydrogen production overcomes many of the infrastructural barriers facing a transition to hydrogen.
- *Centralized architectures*: Centralized systems focus on hydrogen use in road transport and envisage local hydrogen pipeline grids linking early demonstration projects and fleet vehicle refueling depots, creating 'hydrogen corridors' in areas of high demand. Energy is transferred to hydrogen production units (in homes or on forecourts) either as electricity or natural gas.<sup>25</sup>

McDowall and Eames also note that many studies envisage a final mix of centralized and decentralized architectures, with pipelines in areas of strong demand, and with both centralized and decentralized production supplying the hydrogen market. "Despite uncertainty about how a hydrogen economy will emerge and evolve," they conclude, "a series of 'promising niches' were identified as playing important roles in a transition."<sup>26</sup>

There is important dissension on the point of timeframe, particularly concerning the unchallenged acceptance of conventional wisdom about the pace of hydrogen's technological development and adoption rate. Kurani, et. al. (2003) speculate about a convergence of vehicles and lifestyles that could rapidly accelerate FCV use:

"...we propose that the next supporting infrastructure built by modern societies will be a system that fully integrates automobility, electricity, and information. This will be accomplished, in part, by the transformation of automobiles from their current design and role as primarily mobility tools...FCVs will gain competitive advantage in the market if hydrogen and fuel cells are the best energy carriers and converters to power integrated information-mobility-electricity platforms. FCVs may also be afforded further competitive advantages by policies that are both sensitive to automobiles new role as mobile activity locales and create socially sanctioned rewards for progress toward the collective benefits which are the real goals of a transition to hydrogen."<sup>27</sup>

Perhaps what is most interesting about this speculation is the data they present about geometric adoption of mobile phones and Internet use. While it took the telephone 75 years to take over the U.S., cell phones streaked across the nation in a decade. Between 1995 and 2002, Internet users in the U.S. increased from a few million to almost 150 million. In an age of astounding technological escalation, it is difficult to know how quickly a new technology will spread, particularly if it is simultaneously serving multiple needs.

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<sup>25</sup> pp. 1243-44

<sup>26</sup> p. 1248

<sup>27</sup> p. 3

Joan Ogden, of Princeton University's Center for Energy and Environmental Studies, observes that "the conventional wisdom that hydrogen infrastructure is much more capital-intensive than methanol and gasoline is true only for small market penetration of hydrogen or methanol vehicles."<sup>28</sup>

Lovins and Williams (1999) also challenge the extended timeframe for hydrogen adoption, noting: "Transitional paths to fuel cell-powered road vehicles and to a wider hydrogen economy are conventionally assumed to be slow, costly, and difficult, due to two main obstacles:

1. A large new infrastructure for producing and distributing bulk hydrogen, costing tens or hundreds of billions of dollars for the United States alone.
2. Technological breakthroughs in hydrogen storage presumed to be needed because the tankage required for onboard storage of compressed hydrogen gas is currently too bulky to fit acceptably into light and medium vehicles."<sup>29</sup>

They go on to propose Hypercars, "ultralight-hybrid vehicles whose inherently high efficiency permits their fuel-cell stacks to rely on conveniently compact onboard tanks of compressed gaseous H<sub>2</sub>...and integration of fuel-cell market development in an interaction between vehicles and buildings."<sup>30</sup>

"...changing both assumptions can yield an effective transitional strategy to the widespread use of hydrogen... Starting with very efficient vehicles, and properly integrating the deployment of fuel cells in vehicles and in building, can yield a transition to hydrogen that is rapid, relies on established technologies, avoids most of the normally presumed difficulties, and should prove profitable at each step."<sup>31</sup>

The introduction of an interactive energy relationship between vehicles and buildings (which consume two-thirds of the nation's energy) decentralizes the power system and spreads development costs over hundreds of millions of uses. While their "Hypercars" may never come into use, the freshness of their thinking creates a new paradigm for market entry and growth.

Dunn (2001) dissents about timing as well, noting a transitional role for natural gas:

"One of the most significant obstacles to realizing the full promise of hydrogen is the prevailing perception that a full-fledged hydrogen infrastructure—the system for producing, storing, and delivering the gas—would immediately cost hundreds of billions of dollars to build, far more than a system based on liquid fuels such as gasoline or methanol. In the past several years, a number of scientists have openly challenged the conventional wisdom of the incremental path. Their research suggests that the direct use of hydrogen is in fact the quickest and least costly route—for the consumer and the environment—toward a hydrogen infrastructure. Their studies point to an alternative path that would initially use the existing infrastructure for natural gas—the cleanest fossil fuel, and the fastest growing in

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<sup>28</sup> Dunn (2001), p. 58

<sup>29</sup> p. 2

<sup>30</sup> p. 2

<sup>31</sup> p. 2

terms of use—and employ fuel cells in niche applications to bring down their costs to competitive levels, spurring added hydrogen infrastructure investment.”<sup>32</sup>

In its *Hydrogen Commercialization Plan* (US NHA 2004), the U.S. National Hydrogen Association also sees a role for natural gas in the transitional period to the hydrogen economy in which it is used to power stationary distributed power generators.

“The natural gas-powered stationary fuel cell system also is projected to be cost-competitive...especially for co-generation applications where the customer utilizes the waste heat from the fuel cell...the stationary fuel cell has the advantage for helping to develop fuel cell technology, which may assist fuel cell vehicle technology. The natural gas-powered stationary fuel cell will help to reduce the manufacturing cost of steam-methane reformers and gas cleanup systems, both of which will be needed to supply hydrogen for the hydrogen vehicle market.”

Among the emission benefits cited for natural gas:

- NGVs can reduce exhaust emissions of:
  - Carbon monoxide (CO) by 70%.
  - Non-methane organic gas (NMOG) by 87%.
  - Nitrogen oxides (NOx) by 87%.
  - Carbon dioxide (CO<sub>2</sub>) by almost 20% below gasoline.
- NGVs producing only one-sixth the NOx of comparable diesel engines.
- Natural gas contains less carbon than other fossil fuels, producing up to 20% less greenhouse gas emissions than comparable gasoline vehicles, and up to 15% less than comparable diesel vehicles.
- CNG dissipates into the atmosphere in the event of an accident. Natural gas has a high ignition temperature (about 1,200 degrees F), is not toxic or corrosive, and will not contaminate ground water. (NGVA, 2006)

According to the Natural Gas Vehicle Association:

- Over 150,000 NGVs are on U.S. roads.
- Over 1,500 NGV filling stations are in the U.S., with more than half available for public use.
- Natural gas costs, on average, one-third less than conventional gasoline at the pump.
- Roughly 22% of all new transit bus orders are for natural gas. (NGVA, 2006)

In that natural gas is the major source for hydrogen production worldwide, it is already playing a role in the transition to hydrogen. Even noting that natural gas is a fossil fuel and that production of hydrogen from natural gas releases CO<sub>2</sub>, many see a partnership between natural gas and hydrogen as a bridge to a hydrogen economy. One of the most significant is the use of Hythane® fuel to power converted natural gas vehicles.

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<sup>32</sup> p. 11

### Hythane® Fuel

Hythane® is a patented optimal blend of natural gas and hydrogen gas (93% NG to 7% H<sub>2</sub> by energy) developed for internal combustion, fuel cells, and turbine engines that dramatically reduces harmful smog emissions. As an environmental fuel, Hythane® leverages the benefits of hydrogen in that it improves an already clean energy source—natural gas—making it cleaner. From an economic standpoint, Hythane® is significantly less expensive than diesel fuel or gasoline. Hythane® offers a transitional solution today from a fossil fuel economy to a hydrogen economy, utilizing infrastructure and investments to accelerate a pure hydrogen solution.

Projects using Hythane® and Hythane® derivatives in truck and bus fleets are underway or awaiting funding in many U.S. cities (New York, Syracuse, Albany, Niagara Falls, Las Vegas, Barstow, Santa Monica, and Sacramento). In California, the Hydrogen Highway initiative is seeking to construct a Hythane® fueling station, San Francisco International Airport has secured funds to convert its shuttle bus fleet to run on Hythane®, and Los Angeles Airport is reviewing a proposal to convert its shuttle buses to Hythane®. In Canada, Vancouver offers a public Hythane® station, and Montreal city buses run on Hythane®. The SunLine Bus Company has used Hythane® buses in the U.S. and Canada for years. National programs are underway in India and China.

Along with fleets where a centralized fueling station is used, Hythane® is seen as:

- An efficient, readily-available, and clean-burning fuel for power generation on a global basis, even in remote areas that merchant gas providers can't currently serve.
- An excellent candidate as a locomotive fuel in countries where increasing populations and urban pollution are combining to pose serious health threats.

### India's Hydrogen Roadmap

To reach its national goal of transitioning to a hydrogen economy, India is converting its fleet of 500,000 public buses to run on Hythane®. Agreements between its largest engineering company, largest bus manufacturer, and Gujarat State Petroleum have put the pieces into place to secure a durable national consensus about the direction of hydrogen policy. Later this year, the first public hydrogen fueling station will open in Delhi at one of India's busiest natural gas fueling stations. The station will produce, store, blend, and dispense Hythane® as well as pure hydrogen to power natural gas vehicles, including buses, cars, and trucks. Two major Hythane® bus demonstration projects in Gujarat and in Mumbai during 2008 will be a springboard for commercial rollout of thousands of hydrogen/Hythane® fueling stations across India.

India's roadmap to a hydrogen economy is a model for other nations. As the world tunes into the 2008 Summer Olympics, there will be much commentary about the extreme environmental hazards now plaguing many Chinese cities. In the U.S., Los Angeles presents a danger to the health of its citizens and visitors, and many national airports are localized reproductions of cities in India and China. Europe and South America will be watching India's bold steps as well.

## V. Hydrogen Policy Frameworks

McDowall and Eames' (2006) review of hydrogen policy literature finds four most commonly advocated policy measures:

- Increased R&D funding.
- Infrastructure development.
- Public education.
- Tax incentives for hydrogen fuel vehicles.<sup>33</sup>

The policy recommendations in DOE's *National Hydrogen Energy Roadmap* (U.S. Department of Energy, 2002) are the template for our current federal efforts:

**Production:** Efforts should focus on improving existing commercial processes such as steam methane reformation, multifuel gasification, and electrolysis. Development should continue on advanced production techniques such as biological methods and nuclear or solar powered thermochemical water-splitting.

**Delivery:** Initial efforts should focus on development of better components for existing delivery systems, such as hydrogen sensors, pipeline materials, compressors, and high-pressure breakaway hoses. To address the "chicken and egg" (demand/supply) dilemma, demonstrations should test various hydrogen infrastructure components for both central and distributed systems in concert with end-use applications.

**Storage:** Efforts should focus on improving existing commercial technologies, including compressed hydrogen gas and liquid hydrogen, and exploring higher-risk storage technologies involving advanced materials (such as lightweight metal hydrides and carbon nanotubes).

**Conversion:** Research and development are needed to enhance the manufacturing capabilities and lower the cost of fuel cells as well as to develop higher-efficiency, lower-cost reciprocating engines and turbines. Efforts should focus on developing profitable business models for distributed power systems, optimizing fuel cell designs for mobile and stationary applications, and expanding tests of hydrogen-natural gas blending for combustion.

**Applications:** Consumers should be able to use hydrogen energy for transportation, electric power generation, and portable electronic devices such as mobile phones and laptop computers. Key consumer demands include safety, convenience, affordability, and environmental friendliness. Opportunities should be identified to use hydrogen systems in facilities for distributed generation, combined heat and power, and vehicle fleets. Supportive energy and environmental policies should be implemented at the federal, state, and local levels.

**Education and Outreach:** Hydrogen energy development is a complex topic, and people are uncertain about impacts on the environment, public health, safety, and energy security. Informing the public through educational and training materials, science curricula, and public outreach programs will help garner public acceptance for hydrogen-related products and services.

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<sup>33</sup> p. 1246

**Codes and Standards:** Uniform codes and standards for the design, manufacture, and operation of hydrogen energy systems, products, and services can dramatically speed the development process from the laboratory to the marketplace.<sup>34</sup>

Three other major recommendations have been added in subsequent policy updates:

**Technology Validation:** Hydrogen can 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.

**Systems Analysis:** Evaluate existing and emerging technologies through multiple pathways utilizing a fact-based analytical framework to guide the selection and evaluation of R&D projects and to provide a basis for estimating the potential value of research efforts.

**Systems Integration:** Understand the complex interactions between components, systems costs, environmental impacts, societal impacts, and system trade-offs. Identify and analyze these interactions to enable evaluation of alternative concepts and pathways to result in well-integrated and optimized hydrogen and fuel-cell systems. (U.S. Department of Energy & U.S. Department of Transportation, 2006)

The National Renewable Energy Laboratory (Arvizu, 2008) urges: “a balanced R&D program is needed which:

- Introduces hydrogen and FCVs to early markets to stimulate the infrastructure—even with non-optimum technologies.
- Acknowledges criticality of the longer term hydrogen production goals and keeps that R&D funded and viable.”<sup>35</sup>

Asked by DOE to examine technical and policy issues surrounding the U.S. hydrogen economy, including the DOE R&D program, The National Research Council (NRC) concluded:

Systems analysis is needed to coordinate the different paths within the hydrogen program and integrate them with other DOE energy efforts. DOE should continue the hydrogen initiative and develop a systems analysis approach to assess costs, options, research results, and provide a means to balance the short-, mid-, and long-term R&D directions and objectives.

Fuel cell vehicle technology costs will have to be less than \$100 per kilowatt. Increased R&D funding is needed to seek breakthroughs in on-board hydrogen storage, fuel cell costs, and materials for increased durability.

DOE should put greater emphasis on infrastructure and delivery. Such areas as storage requirements, hydrogen purity, pipeline materials, compressors, leak detection, and permitting need attention. In addition, exploratory research on new hydrogen delivery concepts needs additional funding. Also, DOE should accelerate work on codes, standards, and permitting.

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<sup>34</sup> p. iii-iv

<sup>35</sup> Slide 17

DOE's efforts on hydrogen and fuel cell technology will benefit from tighter coupling with the carbon capture and storage (sequestration) program. The hydrogen program should participate in all of the early carbon sequestration projects that address difficult institutional and public acceptance issues.

Commenting on DOE's hydrogen R&D effort, NRC found:

- DOE's hydrogen program has progressed well but the plan needs better integration across all DOE programs. Priorities are unclear. The program has tried to establish R&D activities in too many areas, resulting in a somewhat unfocused program. Prioritizing efforts within and across program areas is extremely important.
- The program should establish partnerships with a broader range of academic and industrial organizations and an independent review process.
- The program should shift some development toward exploratory research, particularly in on-board hydrogen storage, photo-electrochemical production, delivery systems, pipeline materials, electrolysis, and material science.
- The following areas should receive increased R&D emphasis: fuel cell vehicle development, distributed hydrogen generation, infrastructure analysis, carbon sequestration, the FutureGen project, and CO<sub>2</sub>-free energy technologies. (National Research Council, National Academy of Engineering, 2004)<sup>36</sup>

DOE has identified "critical-path" technologies required to develop a hydrogen infrastructure:

- More compact, lighter weight, lower cost, safe and efficient higher 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 production.
- Design materials that maximize the safety of hydrogen use. (U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2007)<sup>37</sup>

DOE has also set specific milestones to achieve hydrogen technology readiness:

- Hydrogen produced from diverse, domestic resources at \$2.00-\$3.00 per gallon of gasoline equivalent.<sup>38</sup>
- On-board hydrogen storage systems with improved capacity to enable a driving range greater than 300 miles for most light-duty vehicles.
- Polymer electrolyte-membrane (PEM) automotive fuel cells that cost \$30-\$45 per kilowatt and deliver 5,000 hours of service. (U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2007)<sup>39</sup>

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<sup>36</sup> p. 2-3

<sup>37</sup> p. ES-3

<sup>38</sup> The average cost of gasoline in the U.S. (May 2008) is close to \$4.00 per gallon, creating some leeway in this goal.

<sup>39</sup> p. iv

## VI. A U.S. Hydrogen Policy

When President Kennedy set the nation on a path to the moon in May 1961, it was done with bold language and scant knowledge of how it would be achieved. Declaring that it should be accomplished “before the decade is out,” the Apollo program leaped to the top of America’s national agenda. Just eight years later, Neil Armstrong stepped onto the lunar surface, taking “one giant leap for mankind.”

We are tantalizingly close to reaching the break-out technologies at market-creating costs that will propel widespread hydrogen use in vehicles, buildings and residences, and portable electronics. However, we are far short of the national resolve needed to cover the remaining ground before it is covered by someone else. As Dunn (2001) notes:

“Hydrogen receives a fraction of the research funding that is allocated to coal, oil, nuclear, and other mature, commercial energy sources. Within energy companies, the hydrocarbon side of the business argues that oil will be dominant for decades to come, even as other divisions prepare for its successor. And very little has been done to educate people about the properties and safety of hydrogen, even though public acceptance or lack thereof, will in the end make or break the hydrogen future.

“Investments made today will heavily influence how, and how fast, the hydrogen economy emerges in coming decades. As with creating the Internet, putting a man on the moon, and other great human endeavors, it is the cost of inaction that should most occupy the minds of our leaders now, at the dawn of the hydrogen (era).”<sup>40</sup>

McDowall and Eames’ (2006) review of hydrogen policy and visioning literature causes them to conclude: “...hydrogen generally emerges slowly or not at all in ‘Business as Usual’ scenarios...rapid penetration of hydrogen occurs only when there is strong governmental support.”<sup>41</sup> Dunn (2001) concurs: “Indeed, without aggressive energy and environmental policies, the hydrogen economy is likely to emerge along the incremental path, and at a pace that is inadequate for dealing with the range of challenges posed by the incumbent energy system.”<sup>42</sup>

Climate change, the price of oil, depleting fossil supplies, and the world’s growing appetite for fuel and power have moved U.S. energy policy into even greater prominence. Cutting across virtually every domestic and international issue from defense to the economy to the environment, there is no more pressing concern today. While there is no magic bullet to resolve our energy needs, hydrogen is the preeminent solution. It is time to put the nation on the path to a hydrogen economy with the same commitment that took us to the moon.

To use the Apollo program as guidance for estimating the proper scale of an ambitious national program that is highly technical and contains many speculative elements, we start with its cost in 1960s dollars. NASA estimated the cost to the U.S. Congress in 1966 at \$22.7 billion. NASA History Web Curator Steve Garber estimates the final cost

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<sup>40</sup> p. 12-13

<sup>41</sup> p. 1243

<sup>42</sup> pp. 12

at \$20 to \$25 billion.<sup>43</sup> Using a GDP calculator to bring this figure to modern dollars, the estimate is around \$120 billion.<sup>44</sup> Presently, the entire annual DOE budget is about \$25 billion. The slice allocated for hydrogen technologies in FY 2009 is \$266 million, an amount guaranteed to produce incremental results.

#### A Hydrogen Policy Platform

We propose these broadly stated planks for a national U.S. hydrogen policy platform to be adopted by the national parties and vigorously advanced in the 2008 presidential campaign:

- I. Commit the nation to securing hydrogen technology supremacy within a decade, and declare this as a top priority of the new administration.
- II. Allocate \$100 billion over four years (\$25 billion a year) to the development of hydrogen technologies. Locate these funds within the DOE Hydrogen Program, focusing on fuel cells, storage, production, safety, and codes and standards.
  - The goal of the transportation fuel cell work is to achieve \$30 per kilowatt technology with 5,000 hours of service.
  - The on-board storage goal is a driving range of greater than 300 miles.
  - The transportation production goal is to reach costs of \$3 per gallon of gasoline equivalent (untaxed) across multiple feedstocks and technologies.
  - The goal of the stationary fuel cell work is to reach 50% efficiency with a lifetime of 50,000 hours.
  - The portable fuel cell goal is to achieve energy density of 1000 watt-hours per liter.
  - Each of these goals is to be achieved by 2012 or sooner.
- III. Select a leading figure from the private sector to head a Hydrogen Initiative to identify and invest a matching \$100 billion from private industry (\$25 billion per year) on hydrogen vehicle development, fueling stations, and stationary and portable power generation products. Investments in these market-creating categories will augment and leverage government spending, and anticipate and hasten the hydrogen economy. Hydrogen Initiative leadership would develop its own agenda and action plan. A small “C level” council of DOE Hydrogen Program leadership and leadership of the Hydrogen Initiative should be established to support close coordination and communication between the public and private efforts. This mechanism for private sector contribution should be structured to ensure full access and participation by companies large and small to encourage development of the full range of hydrogen technologies and applications. Steps should be taken at the outset to prevent domination by large energy interests with substantial financial resources. Innovation is very often achieved by the small company with a big idea.
- IV. Instruct the Interagency Hydrogen and Fuel Cell Technical Task Force created by the Energy Policy Act of 2005 to review and assess all federal hydrogen programs to determine focus, progress, promise, and efficiency. The inventory should include all carbon capture and containment programs to ensure these are integrated with hydrogen policy. The Task Force should report to the president

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<sup>43</sup> <http://www.measuringworth.com/uscompare/>

<sup>44</sup> Ibid

by mid-2009, recommending which programs should be accelerated and which should be terminated. No program should be allowed to proceed at status quo. This will sharpen federal activity, weeding out unproductive and duplicative programs. The report should also consider how best to integrate hydrogen activities now underway in 38 states with the federal Hydrogen Program.

- V. Establish a discrete program within the DOE Hydrogen Program to focus on CO<sub>2</sub>-free and renewable hydrogen production. Hydrogen production from current feedstocks provides an effective transition to the hydrogen economy but falls short of realizing the full promise of zero emissions energy.
- VI. Reevaluate the role of nuclear technology in the U.S. energy portfolio in light of its potential to contribute to economic renewable hydrogen production from water.
- VII. Build consumer acceptance and demand with demonstration projects in U.S. cities with the worst air quality (<http://www.lungusa.org/>) by converting public bus fleets and public service vehicles to operate on hydrogen or Hythane to show the benefits of hydrogen-based fuel. Collaborating with the Ad Council (<http://www.adcouncil.org/>) to develop and fund a sustained two-year hydrogen energy campaign that will make “hydrogen” a household word synonymous with clean, safe, abundant energy. These projects should be undertaken jointly by the federal Hydrogen Program and the private Hydrogen Initiative.
- VIII. Make the case for hydrogen in the new president’s inaugural address, formally launching the new national program. Speak about it frequently and prominently from the “bully pulpit,” and report on its progress in detail each year in the State of the Union Address.

#### Funding

Allocating \$25 billion a year in funding is no easy task, even in the age of a \$3 trillion federal budget. Certainly a portion of the \$25 billion could be raised by an increase in the \$18.4 cent federal gas tax. A case can be made that U.S. gasoline is inexpensive relative to other parts of the world and we will never move to alternatives until gasoline costs even more. A reduction in tax breaks to oil companies might also be considered. The estimated \$18 billion in oil company tax reductions in the 2004 and 2005 energy bills would make a significant contribution toward funding hydrogen development.

There is no better time to make a bold spending proposal than in the first budget of a newly elected president. Getting to the hydrogen economy should be among the few big ideas that Congress and the American people concede to the new president.

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## Appendix A: Getting To A Hydrogen Energy System

Production—Government-industry coordination on hydrogen production systems is required to lower overall costs, improve efficiency, and reduce the cost of carbon sequestrations. Better techniques are needed for both central-station and distributed hydrogen production. Efforts should focus on improving existing commercial processes such as steam methane reformation, multifuel gasification, and electrolysis. Development should continue on advanced production techniques such as biological methods and nuclear- or solar-powered thermochemical water-splitting.

Delivery—A greatly expanded distributed infrastructure will be needed to support the expected development of hydrogen production, storage, conversion, and applications. Initial efforts should focus on the development of better components for existing delivery systems, such as hydrogen sensors, pipeline materials, compressors, and high-pressure breakaway hoses. Cost, safety, and reliability issues will influence the planning, design, and development of central versus distributed production and delivery. To address the “chicken and egg” (supply/demand) dilemma, demonstrations should test various hydrogen infrastructure components for both central and distributed systems in concert with end-use applications (e.g., fueling stations and power parks).

Storage—Hydrogen storage is a key enabling technology. None of the current technologies satisfy all of the hydrogen storage attributes sought by manufacturers and end users. Government-industry coordination on research and development is needed to lower costs, improve performance, and develop advanced materials. Efforts should focus on improving existing commercial technologies, including compressed hydrogen gas and liquid hydrogen, and exploring higher-risk storage technologies involving advanced materials (such as lightweight metal hydrides and carbon nanotubes).

Conversion—Conversion of hydrogen into useful forms of electric and thermal energy involves use of fuel cells, reciprocating engines, turbines, and process heaters. Research and development are needed to enhance the manufacturing capabilities and lower the cost of fuel cells as well as to develop higher-efficiency, lower-cost reciprocating engines and turbines. Efforts should focus on developing profitable business models for distributed power systems, optimizing fuel cell designs for mobile and stationary applications, and expanding tests of hydrogen-natural gas blending for combustion. Research is required to expand fundamental understanding of advanced materials, electrochemistry, and fuel cell stack interfaces and to explore the fundamental properties of hydrogen combustion.

Applications—Ultimately, consumers should be able to use hydrogen energy for transportation, electric power generation, and portable electronic devices such as mobile phones and laptop computers. Cost and performance issues associated with hydrogen energy systems will need to be addressed in tandem with customer awareness and acceptance. Key consumer demands include safety, convenience, affordability, and environmental friendliness. Efforts should focus on understanding consumer preferences and building them into hydrogen system designs and operations. Opportunities should be identified to use hydrogen systems in facilities for distributed generation, combined heat and power, and vehicle fleets. Supportive energy and environmental policies should be implemented at the federal, state, and local levels.

Education and Outreach—Hydrogen energy development is a complex topic and people are uncertain about the impacts on the environment, public health, safety, and energy security. Ultimately, consumer preferences drive the choices made in energy markets, technology development, and public policy. Informing the public through educational and training materials, science curricula, and public outreach programs will help garner public acceptance for hydrogen-related products and services.

Codes and Standards—Uniform codes and standards for the design, manufacture, and operation of hydrogen energy systems, products, and services can dramatically speed the development process from the laboratory to the marketplace. Government-industry coordination can accelerate codes and standards processes, which must also span national boundaries and be accepted by international bodies to achieve global acceptance.

(U.S. Department of Energy, 2002)

## Appendix B: Hydrogen Energy System Elements and Challenges

<b>Hydrogen Infrastructure Elements</b>	<b>Key Hurdles</b>
<p><b>Production</b>—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</p>	<ul style="list-style-type: none"> <li>• Low cost hydrogen production techniques</li> <li>• Low cost and environmentally sound carbon capture and sequestration technologies</li> <li>• Advanced hydrogen production techniques from fossil, renewable, and nuclear resources</li> </ul>
<p><b>Delivery</b>—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.</p>	<ul style="list-style-type: none"> <li>• Lower-cost hydrogen transport technology</li> <li>• Appropriate, uniform codes and standards</li> <li>• Right-of-way for new delivery systems</li> <li>• High investment risk of developing hydrogen delivery infrastructure</li> </ul>
<p><b>Storage</b>—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.</p>	<ul style="list-style-type: none"> <li>• Low cost, high capacity, lightweight, and low-volume hydrogen storage systems</li> </ul>
<p><b>Conversion</b>—Fuel cells produced in high volumes would be cost-competitive, durable, and reliable and provide clear advantages in energy efficiency and emissions.</p>	<ul style="list-style-type: none"> <li>• Low cost, durable, and reliable fuel cells that can be mass-produced</li> </ul>
<p><b>Technology Validation</b>—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.</p>	<ul style="list-style-type: none"> <li>• Successful field test and demonstrations of integrated systems that meet customer requirements.</li> <li>• Supportive public policies to stimulate infrastructure and market readiness</li> </ul>
<p><b>Safety, Codes and Standards</b>—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.</p>	<ul style="list-style-type: none"> <li>• Fuel gas code that includes hydrogen</li> <li>• Uniform safety standards for certification of fuel cell vehicles, stationary power facilities, and portable devices.</li> </ul>
<p><b>Public Education</b>—Businesses, government agencies, and the public may choose to use hydrogen to safely and conveniently power their vehicle; 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.</p>	<ul style="list-style-type: none"> <li>• Widespread understanding of, and confidence in, the safe use of hydrogen as an energy carrier</li> <li>• Access to accurate, objective information about hydrogen and fuel cell technologies</li> <li>• Education and training for emergency responders and code officials</li> </ul>

(U.S. Department of Energy & U.S. Department of Transportation, 2006)

## Appendix C: The U.S. Hydrogen Program

<b>Key Activity</b>	<b>Hydrogen Program Focus</b>
Production	Advanced cost-effective, efficient production of hydrogen from renewable, fossil, and nuclear energy resources.
Delivery	Distribution of hydrogen from centralized or distributed sites of production.
Storage	Materials R&D and on-board vehicular hydrogen storage systems that will allow for a driving range of 300 miles or more.
Fuel Cells	Materials and component R&D to reduce cost and improve durability of PEM fuel cells for transportation and stationary applications.
Manufacturing	High-volume fabrication and assembly processes to reduce cost and develop a domestic supplier base.
Technology Validation	Field tests and evaluation of hydrogen and fuel cell technologies, and technical validation of integrated systems in real-world environments.
Safety	Working to ensure safety in hydrogen production and use by applying lessons learned and best practices within the Program and promulgating that experience outside the Program.
Codes and Standards	Working with Standard Development Organizations and Code Development Organizations to facilitate the development of hydrogen technology codes and standards. Also supports R&D that provides a basis for the requirements cited in codes and standards.
Education	Educating the public, as well as key target audiences—teachers and students, state and local government representatives, safety and code officials, and potential commercial end-users—about hydrogen and fuel cell technologies.
Systems Analysis	Evaluating existing and emerging technologies through multiple pathways utilizing a fact-based analytical framework to guide the selection and evaluation of R&D projects and to provide a basis for estimating the potential value of research efforts.
Systems Integration	Understanding the complex interactions between components, systems costs, environmental impacts, societal impacts, and system trade-offs. Identifying and analyzing these interactions will enable evaluation of alternative concepts and pathways and result in well-integrated and optimized hydrogen and fuel-cell systems.

(U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2007)

Appendix D: State and Regional Hydrogen Initiatives

<b>Organization</b>	<b>State (Province)</b>
California Fuel Cell Partnership	CA
California Hydrogen Business Council	CA
California Stationary Fuel Cell Collaborative	CA
Clean Energy States Alliance (CESA)	CT, IL, MA, MN, NJ, NY, OH, OR, PA, RI, WI
Connecticut Clean Energy Fund	CT
Connecticut Hydrogen Fuel Cell Coalition	CT
East Tennessee Hydrogen Initiative	TN
Florida Department of Environmental Protection	FL
Florida Hydrogen Business Partnership	FL
Florida Hydrogen Initiative	FL
Fuel Cell South	SC
Fuel Cell Texas	TX
H2USA Centers	FL, NY
Hudson Valley Clean Communities Coalition	NY
Hydrogen Technology Education Consortium for the South (HyTEC)	FL, GA, NC, SC
Maine Hydrogen Energy Center	ME, CT, NY, MA, NH, VT
Massachusetts Hydrogen Coalition, Inc.	MA
Mid-Atlantic Hydrogen Coalition	VA, MD, PA, NJ
Mountain States Hydrogen Business Council	AZ, CO, NM, NV, UT
National Hydrogen Association	U.S.A.
National Renewable Energy Laboratory	CO
New Jersey Hydrogen Learning Center	NJ
New York State Hydrogen Energy Vision and Roadmap	NY
NextEnergy	MI
Northeast Hydrogen Alliance (NeHA)	NH, VT, ME, MA, NY, CT
Northwest Hydrogen Alliance	WA
Ohio Fuel Cell Coalition	OH
Ohio Fuel Cell Supply Chain Project	OH
Public Fuel Cell Alliance	CT, DE, MA, NJ, OH, PA, RI
Red River Valley Research Corridor	ND
South Carolina Hydrogen and Fuel Cell Alliance	SC
South Carolina Next Energy Initiative	SC
Southern Fuel Cell Coalition	GA, TN, FL, AL, MS, LA, TX, NC, SC, VA, KY
Texas Hydrogen Coalition	TX
Upper Midwest Hydrogen Initiative	IA, Manitoba, MN, ND, SD, WI
Virginia Clean Cities	VA, MD, PA
Virginia-Maryland Hydrogen Technology Education Center (H2TEC)	MD, VA
West Penn Power Sustainable Energy Fund	PA

(National Hydrogen Association, 2008)