Toward a More Secure
and Cleaner Energy
Future for America

A National Vision of America's Transition to a Hydrogen Economy — To 2030 and Beyond

Based on the results of the
National Hydrogen Vision Meeting
Washington, DC
November 15-16, 2001

February 2002

United States Department of Energy

A Call for Partnership

This document outlines a vision for America's energy future—a more secure nation powered by clean, abundant hydrogen. This vision can be realized if the Nation works together to fully understand hydrogen's potential, to develop and deploy hydrogen technologies, and to produce and deliver hydrogen energy in an affordable, safe, and convenient manner.

President Bush's National Energy Policy says, "In the long run, alternative energy technologies such as hydrogen show great promise." In response, Energy Secretary Spencer Abraham recently stated, "The President's Plan directs us to explore the possibility of a hydrogen economy." This vision document is a first step. It will be used as a foundation for formulating the elements of a National Hydrogen Energy Roadmap.

Hydrogen is a long-term solution to America's energy needs, with near-term possibilities. Efforts to achieve our energy goals need to begin now and continue with a sustained commitment over the next several decades. It is important to strengthen our partnerships among government, industry, and others in order to improve hydrogen technologies and systems, and to build the infrastructure—both physical and institutional—that will be needed in the years ahead. The tragic events of September 11, 2001, highlight the urgency of making progress toward greater energy security.

The efforts of the 53 business executives, Federal and State energy policy officials, and leaders of universities, environmental organizations, and National Laboratories who contributed to the development of this vision document by offering their views at the National Hydrogen Vision Meeting are deeply appreciated. A nationwide effort to achieve the hydrogen vision can only succeed through strong public-private partnerships, to address the issues involved in the introduction of a new vehicle infrastructure and distributed generation systems. It is a broad and encompassing task with major national benefits. All affected stakeholders need to join together in this most important endeavor.

Executive Summary

On November 15-16, 2001, 53 senior executives representing energy and transportation industries, universities, environmental organizations, Federal and State government agencies, and National Laboratories met to discuss the potential role for hydrogen systems in America's energy future. (A list of the participants can be found in the appendix.) The intent of the meeting was to identify a common vision of the "hydrogen economy," the time frame in which such a vision could be expected to occur, and the key milestones that would need to be accomplished to get there.

Based on the ideas and suggestions put forth by the participants during the meeting, this document presents a national vision for hydrogen to become a premier energy carrier, like electricity, for Americans. It will be used by various stakeholders including industry, policy makers, and researchers as the coordinating foundation for formulating future actions leading to a hydrogen economy. The meeting proceedings, which include the presentations and summaries of the notes from the facilitated breakout sessions, can be downloaded at www.eren.doe.gov/hydrogen.

National Vision

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.

Major Findings

- Hydrogen has the potential to solve two major energy challenges that confront America today: reducing dependence on petroleum imports and reducing pollution and greenhouse gas emissions.

- There is general agreement that hydrogen could play an increasingly important role in America's energy future. Hydrogen is an energy carrier that provides a future solution for America. The complete transition to a hydrogen economy could take several decades.

- The transition toward a so-called "hydrogen economy" has already begun. We have a hydrocarbon economy, but we lack the know-how to produce hydrogen from hydrocarbons and water, and deliver it to consumers in a clean, affordable, safe, and convenient manner as an automotive fuel or for power generation.

- The "technology readiness" of hydrogen energy systems needs to be accelerated, particularly in addressing the lack of efficient, affordable production processes; lightweight, small volume, and affordable storage devices; and cost-competitive fuel cells.

- There is a "chicken-and-egg" issue regarding the development of a hydrogen energy infrastructure. Even when hydrogen utilization devices are ready for broad market applications, if consumers do not have convenient access to hydrogen as they have with gasoline, electricity, or natural gas today, then the public will not accept hydrogen as "America's clean energy choice."

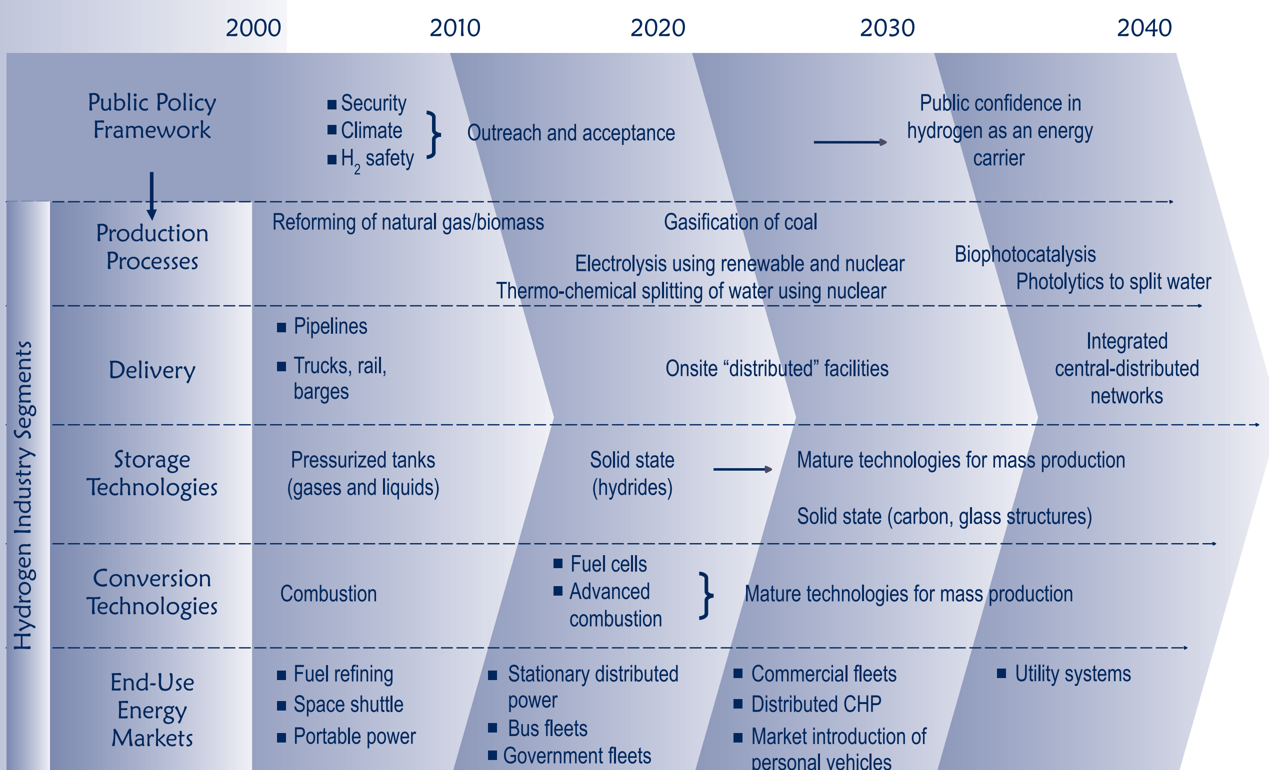
Conclusions

- To achieve significant progress toward the development of hydrogen energy systems, Federal and State governments need to implement and sustain consistent energy policy actions that elevate hydrogen as a priority to meet energy security, energy independence, and climate change challenges.

- A successful effort to achieve the hydrogen vision will require a strong public-private partnership on hydrogen energy development, as called for in the President's National Energy Policy. Efforts must be focused on finding new ways to collaborate on the development and use of hydrogen energy. For example, the Federal government could play a valuable role as first-use "customer."

- A logical next step is the collaborative development of a National Hydrogen Energy Roadmap. This process needs to address research, development, testing, public outreach and education, and codes and standards for hydrogen production, delivery, and use. It should cover both mobile and stationary applications of hydrogen energy systems, and it should involve industry, government, universities, and the National Laboratories.

Overview of the Transition to the Hydrogen Economy



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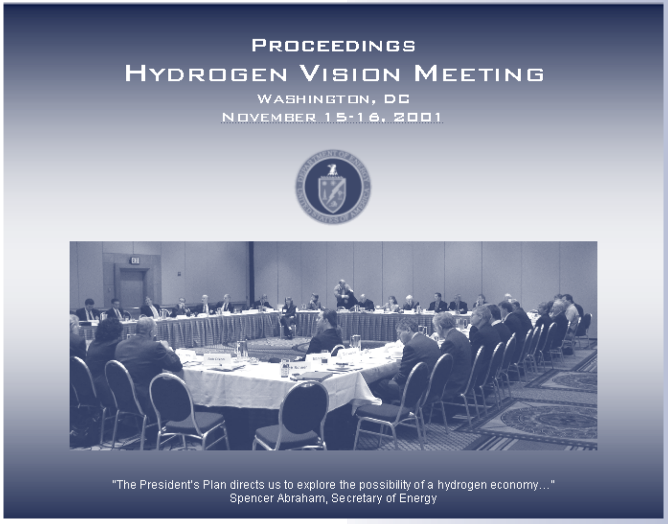
1. Introduction

More than fifty executives from energy-related and transportation industries, Federal and State government agencies, universities, environmental organizations, and National Laboratories participated in the “National Hydrogen Vision Meeting,” which was held in Washington, DC, on November 15 and 16, 2001. (A list of the participants can be found in the appendix.) This document reflects the ideas and priorities put forth by the meeting participants.

The meeting was held in response to specific recommendations in the Bush Administration’s *National Energy Policy*, which was released on May 17, 2001. This comprehensive energy strategy contains 105 recommendations for securing America’s energy future, including the expansion of energy supplies, improvement of infrastructure, modernization of energy conservation, and protection of the environment. In considering long-term energy and climate change solutions, hydrogen is singled out as a “future energy source...that shows great promise...and is compatible with existing energy technologies, such as fuel cells, engines, and combustion turbines.” The report recommends that the U.S. Department of Energy “focus research and development efforts on integrating current programs regarding hydrogen, fuel cells, and distributed energy.”

A National Hydrogen Vision and Roadmap process was initiated by the U.S. Department of Energy, in partnership with key hydrogen energy and transportation organizations, to address this recommendation. The goals of the vision and roadmap are to identify areas of agreement and disagreement about hydrogen’s role in America’s energy future, to establish a timeframe in which a hydrogen economy may be realized, and to discuss alternative pathways to achieve the vision. Special emphasis has been placed on public-private partnerships, and joint research, development, demonstration, education, and outreach programs.



The proceedings of the vision meeting, which includes copies of presentations and summaries of the notes from the discussions, is available at www.eren.doe.gov/hydrogen.

While there have been many successful technical meetings on hydrogen research and development programs over the past decade, including semi-annual meetings of the Hydrogen Technical Advisory Panel, this meeting marked the first occasion that a broad cross-section of senior business leaders and energy and environmental officials from across the United States have met to discuss hydrogen energy development and its future as an energy source for America.

A broad range of stakeholders were invited to participate in the vision meeting. The participating non-Federal organizations included energy companies, automobile companies, fuel cell manufacturers, hydrogen equipment manufacturers, State agencies, and environmental organizations. Participating Federal organizations included the Department of Energy, the U.S. Navy, and the National Aeronautics and Space Administration.

The meeting included discussions about the following specific topics:

- Status of today's U.S. hydrogen energy industry
- Factors—both supporting and inhibiting—that will shape future hydrogen energy development
- A vision for the future of the hydrogen energy industry
- What is meant by the term "hydrogen economy," and the most likely time frame(s) in which it may take place
- The key milestones and pitfalls that are likely to be encountered on the path to a "hydrogen economy"
- Ways in which industry and government can form stronger partnerships to address hydrogen energy development

The vision and roadmap process has been a useful technique for organizing research and development partnerships involving the U.S. Department of Energy, industry, the National Laboratories, and universities. The process typically involves a series of meetings attended by industry leaders and visionaries, technical experts, and practitioners to discuss future needs using professional facilitators to guide the discussions. Executive-level participation was emphasized in the development of the vision, and technical managers and practitioners will be encouraged to participate in the development of the roadmap.

2. The Hydrogen Industry Today

The current hydrogen industry is not focused on the production or use of hydrogen as an energy carrier or a fuel for energy generation. Rather, the nine million tons of hydrogen produced each year are used mainly for chemicals, petroleum refining, metals, and electronics. For example, the processes for making gasoline and diesel fuels, such as the breakdown of heavier crude oils and the removal of sulfur, are major users of hydrogen. The production of ammonia, used to make fertilizers, also consumes large amounts of hydrogen.

The use of hydrogen as an energy carrier or major fuel requires development in several industry segments, including production, delivery, storage, conversion, and end-use. The table below provides a list of terms and explanations for hydrogen energy systems. Each industry segment is integral to building a hydrogen-based economy, and the development of one segment relies on corresponding development of all other segments.

Elements of Today's Hydrogen Energy System

Hydrogen Industry Segment	Explanation
Production	■ The production of hydrogen from fossil fuels, biomass, or water ■ Involves thermal, electrolytic, and photolytic processes
Delivery	■ The distribution of hydrogen from production and storage sites ■ Involves pipelines, trucks, barges, and fueling stations
Storage	■ The confinement of hydrogen for delivery, conversion, and use ■ Involves tanks for both gases and liquids at ambient and high pressures ■ Involves reversible and irreversible metal hydride systems
Conversion	■ The making of electricity and/or thermal energy ■ Involves combustion turbines, reciprocating engines, and fuel cells
End-Use Energy Applications	■ The use of hydrogen for portable power in devices such as mobile phones and computers ■ The use of hydrogen for transportation systems such as fuel additives, fuel-cell vehicles, internal combustion engines, and in propulsion systems for the space shuttle ■ The use of hydrogen for stationary energy generation systems, including mission critical, emergency, and combined heat and power applications

Overview

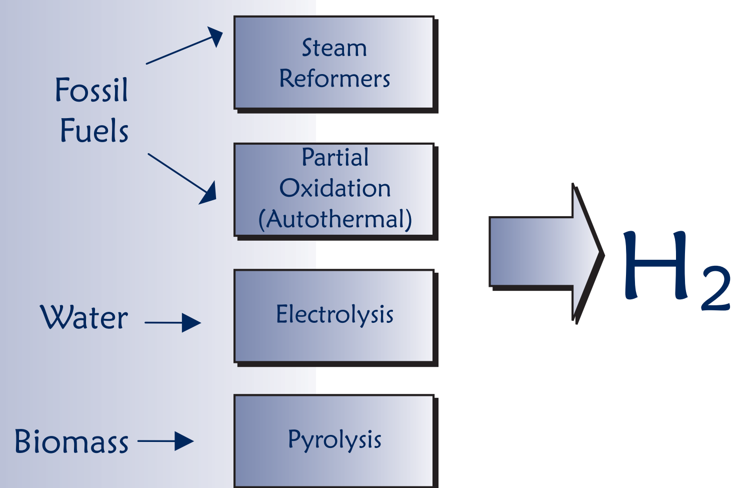
Hydrogen can be produced through thermal, electrolytic, or photolytic processes applied to fossil fuels, biomass, or water. Renewable and nuclear systems can produce hydrogen from water using thermal or electrolytic processes. The thermal production process, which uses steam to produce hydrogen from natural gas or other light hydrocarbons, is most common. This hydrogen is either consumed on site ("captive" hydrogen) or distributed via pipelines or trucks ("merchant" hydrogen). Hydrogen can be stored in its elemental form as a liquid, gas, or as a chemical compound, and is converted into energy through fuel cells or by combustion in turbines and engines. Each of these components of the hydrogen industry is under development. The following sections explain the current status of these technological areas in greater detail.

Production

Although hydrogen is the most abundant element in the universe, it does not naturally exist in its elemental form on Earth. It must be produced from other compounds such as water, biomass, or fossil fuels. Each method of production from these constituents requires energy in some form, such as heat, light, or electricity, to initiate the process.

In the United States, approximately 95 percent of hydrogen is currently produced via steam reforming.[1] Steam reforming is a thermal process, typically carried out over a nickel-based catalyst, that involves reacting natural gas or other light hydrocarbons with steam. This is a three-step process that results in a mixture of hydrogen and carbon dioxide, which is then separated by pressure swing adsorption, to produce pure hydrogen. Steam reforming is the most energy efficient commercialized technology currently available, and is most cost-effective when applied to large, constant loads. Research is being conducted on improving catalyst life and heat integration, which would lower the temperatures needed for the reformer and make the process even more efficient and economical.

Hydrogen Production Alternatives



Partial oxidation (autothermal production) of fossil fuels is another method of thermal production. It involves the reaction of fuel with a limited supply of oxygen to produce a hydrogen mixture, which is then purified. Partial oxidation can be applied to a wide range of hydrocarbon feedstocks, including light hydrocarbons as well as heavy oils and hydrocarbon solids. However, it has a higher capital cost because it requires pure oxygen to minimize the amount of gas that must later be treated. In order to make partial oxidation cost effective for the specialty chemicals market, lower cost fossil fuels must be used. Current research is aimed at improving membranes for better separation and conversion processes in order to increase efficiency, and thus decrease the consumption of fossil fuels.

Hydrogen can also be produced by using renewable and nuclear resources to extract hydrogen from water, but these methods are currently not as efficient or cost effective as using fossil fuels. Biomass can be thermally processed through gasification or pyrolysis to produce hydrogen. Research on nuclear-based hydrogen production is mostly conducted on thermo-chemical processes, which makes use of high reactor exit temperatures. Both are continuing to be developed. Creation of more efficient, less expensive electrolyzers using renewables and nuclear power is also ongoing.

[1] Air Products and Chemicals, Inc.

Delivery

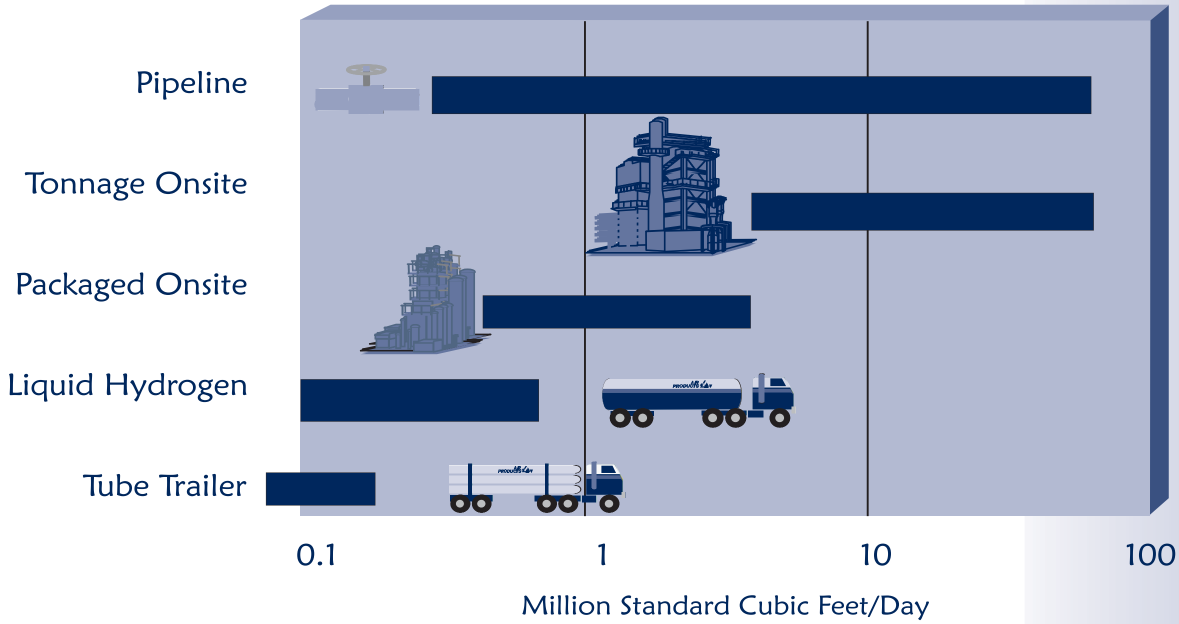
A hydrogen energy infrastructure would include production and storage facilities, structures and methods for transporting hydrogen, fueling stations for hydrogen-powered applications, and technologies that convert the fuel into energy through end-use systems that power buildings, vehicles, and portable applications. This section focuses on existing infrastructure that moves the hydrogen from its point of production to an end-use device.

Today hydrogen is produced primarily in decentralized locations and is used on-site for making chemicals or upgrading fuels. Approximately 17 percent of hydrogen is centrally produced for sale and distribution, and is transported through pipelines or via cylinders and tube trailers.[2] Air Products and Chemicals Inc., Air Liquide Group, Praxair Inc., and the BOC Group are major producers of merchant hydrogen. Together these companies operate about 80 plants in the United States that are dedicated to the production of merchant hydrogen.

Similar to natural gas distribution, pipelines are used to supply hydrogen to customers. Currently hydrogen pipelines are used in only a few areas of the United States. Air Liquide Group, Air Products and Chemicals Inc., and Praxair Inc. operate hydrogen pipelines in Texas, Louisiana, California, and Indiana. Pipelines provide an efficient means for transporting hydrogen. Concerns regarding the weakening of carbon steel pipes in a process called hydrogen embrittlement are being addressed. Alternate delivery forms such as the transport of hydrogen in safe compounds or chemical forms, are being developed to get hydrogen to end-use sites on an as-needed and real time usage basis.

Hydrogen is also distributed via cylinders and tube trailers that are transported by trucks, railcars, and barges. For long-distance distribution of up to 1000 miles, hydrogen is usually transported as a liquid and then vaporized for use on-site. Eleven plants have the capacity to produce 283 tons of liquid hydrogen per day in North America.

Hydrogen Delivery Methods



Source: Air Products and Chemicals, Inc.

[2] Air Products and Chemicals, Inc.

Storage

Hydrogen can be stored as a gas or liquid or in a chemical compound using a variety of technologies.

Compact storage of hydrogen gas in tanks is the most mature storage technology, but is difficult because hydrogen is the lightest element and has very low density under normal conditions. This is addressed through compression to higher pressures or interaction with other compounds. In addition, storage tank materials are advancing—they are getting lighter and better able to provide containment. Some have a protective outside layer to improve impact resistance and safety.

Liquid hydrogen is stored in cryogenic containers, which requires less volume than gas storage. However, the liquefaction of hydrogen consumes large quantities of electric power, equivalent to about one-third the energy value of the hydrogen.

Hydrogen Storage Alternatives

Compressed Fuel Storage
· Cylindrical tanks
· Quasi-conformable tanks
Liquid Hydrogen Storage
· Cylindrical tanks
· Elliptical tanks
Solid State Conformable Storage
· Hydride storage material
· Carbon adsorption
· Glass microspheres

Source: QUANTUM Technologies

Hydrogen can be stored "reversibly" and "irreversibly" in metal hydrides. In reversible storage, metals are generally alloyed to optimize both the system weight and the temperature at which the hydrogen can be recovered. When the hydrogen needs to be used, it is released from the hydride under certain temperature and pressure conditions, and the alloy is restored to its previous state. In irreversible storage, the material undergoes a chemical reaction with another substance, such as water, that releases the hydrogen from the hydride. The byproduct is not reconverted to a hydride.

Laboratory research continues in the development of carbon-based storage systems. Hydrogen storage in carbon structures is achieved chemically in fullerenes or by physical sorption in carbon nanotubes. These processes are controlled through temperature and pressure and are still a long way from development.

Conversion

As mentioned, hydrogen is an energy carrier that requires production by an energy source (e.g., fossil, renewable, or nuclear) using a feedstock (e.g., fossil, biomass, or water) followed by consumption of the hydrogen by a particular end-use device to produce heat or electricity. Hydrogen can be converted to energy via traditional combustion methods and through electrochemical processes in fuel cells.

Combustion

Hydrogen can be combusted in the same manner as gasoline or natural gas. The benefit of using hydrogen combustion over fossil fuel combustion is that it releases fewer emissions—water is the only major byproduct. No carbon dioxide is emitted, and nitrogen oxides, produced by a reaction with the nitrogen in the air, can be significantly lower than with the combustion of fossil fuels. This technology is fairly well developed—both the National Aeronotics and Space Administration (NASA) and the Department of Defense use it for applications such as the space shuttle's main engines and unmanned rocket engines. Other combustion applications are being researched, such as new designs of combustion equipment specifically for hydrogen in turbines and engines. Hydrogen internal combustion engine vehicles are being demonstrated—Ford and BMW made significant progress in advanced Hydrogen Internal Combustion Engine (H2-ICE) vehicles in 2001. Also, the combustion of hydrogen blends is being practiced, as blends have been shown to emit fewer pollutants than pure fossil fuels once the engine is leaned out, and would promote a transition to the combustion of 100 percent hydrogen fuel.

Fuel Cells

Fuel cells utilize the chemical energy of hydrogen to produce electricity and thermal energy. A fuel cell is a quiet, clean source of energy. Water is the only by-product it emits if it uses hydrogen directly. Since electrochemical reactions generate energy more efficiently than combustion, fuel cells can achieve higher efficiencies than internal combustion engines. Current fuel cell efficiencies are in the 40 to 50 percent range, with up to 80 percent efficiency reported when used in combined heat and power applications.

Fuel cells are similar to batteries in that they are composed of positive and negative electrodes with an electrolyte or membrane. The difference between fuel cells and batteries is that energy is not recharged and stored in fuel cells as it is in batteries. Fuel cells receive their energy from the hydrogen or similar fuel that is supplied to them. No charge is thereby necessary.

Fuel cells are characterized by their electrolyte, operating temperature, and level of hydrogen purity required. The following table summarizes the characteristics of various fuel cell types. Phosphoric acid fuel cells are the most developed fuel cells for commercial use. Many of the installed units are used in stationary applications to provide grid support and reliable back-up power, and in transportation applications to power large vehicles such as buses. Proton exchange membrane (PEM) fuel cells are being

Summary of Fuel Cell Types

Fuel Cell	Electrolyte	Operating Temperature (ºC)	Sensitivities to Hydrogen Purity
Proton Exchange Membrane	Solid organic polymer poly-perfluorosulfonic acid	60-100	High sensitivities to impurities, must have <10 ppm CO
Alkaline	Aqueous solution of potassium hydroxide soaked in a matrix	90-100	High sensitivity to carbon dioxide
Phophoric Acid	Liquid phosphoric acid soaked in a matrix	175-200	Sensitive to CO
Molten Carbonate	Liquid solution of lithium, sodium and/or potassium carbonates, soaked in a matrix	600-1000	Low sensitivity to CO, Hydrogen/carbon monoxide mixtures can be used. CO_2 is required
Solid Oxide	Solid zirconium oxide to which a small amount of ytrria is added	600-1000	Low sensitivity to CO, Hydrogen/carbon dioxide/ methane mixtures can be used

developed and tested for use in transportation, stationary, and portable applications. There has been a tremendous upsurge in interest in PEM fuel cells over the past few years, and most major automotive manufacturers are developing fuel cell concept cars. Alkaline fuel cells have been used in military applications, for NASA space missions to provide electricity and drinking water for astronauts, and are being tested for transportation applications. Solid oxide and molten carbonate fuel cells are best for use in generating electricity in stationary combined cycle applications and cogeneration applications in which waste heat is used for cogeneration. They also fit well for portable power and transportation applications, especially large trucks.

Fuel cells have operating advantages for both stationary and mobile applications in that they are quiet and typically have high efficiencies at partial loads. They also have environmental advantages. For example, when pure hydrogen is used as the fuel, there are no emissions of sulphur or nitrogen oxides, or particulates. And if the hydrogen comes from a net-carbon-free renewable or nuclear energy source, the system will also be free of carbon dioxide emissions. The direct conversion of the energy stored in the fuel to electricity in a fuel cell can be achieved at high efficiencies, avoiding limitations of standard heat-to-power cycles used in combustion engines and turbines. Fuel cells are also deployable in combined heat and power applications.

End Use Energy Applications

Hydrogen energy end-use applications include stationary, transportation, and portable devices. As mentioned, the most common current use for hydrogen is in industrial processes such as refineries. It is also used as a fuel at NASA, where the combustion of hydrogen has fueled its space shuttle main engines and propulsion systems for years. Other energy uses are generally limited to research and demonstrations.

One application of hydrogen fuel cells is for distributed generation. A number of UTC Fuel Cell's phosphoric acid fuel cells are operating in locations around the world, providing heat and power for buildings and industrial applications. These units include a reformer component to generate a hydrogen-rich gas from natural gas.

In the transportation sector, a number of fuel cell vehicles are being tested and developed. Vehicular use of hydrogen energy requires a compact power system and refueling stations. Given the current state of hydrogen technologies, city-owned buses are a promising application because they are capable of carrying large tanks of hydrogen and typically refuel at a single location. In March 1998, for example, Chicago became the first city in the United States to use hydrogen fuel cells to power buses in their public transit system.

Prototype Hydrogen Fuel Cell Vehicles

HYUNDAI SANTA FE CA0862

NECAR IV CA0729

FORD P2000 FCV CA0736

GM OPEL ZAFIRA CA1292

TOYOTA FCHC CA1250

HONDA FCX CA1243

Vehicle	Type
2000 GM-Opel Zafira	Light Truck/Van/SUV
1998 Ford P2000 FCV	Mid-size/Full-size
2001 Hyundai Santa Fe/IFC	Light Truck/Van/SUV
2000 Necar	Sub-compact/Compact
Toyota FCHC	Light Truck/Van/SUV
2001 Honda FCX	Sub-compact/Compact

Source: UTC Fuel Cells

Several car manufacturers, including Hyundai, Ford, General Motors, Toyota, Honda, and DaimlerChrysler are developing fuel cell vehicles for personal use. In 2001, the BMW CleanEnergy World Tour demonstrated its fleet of 15 hydrogen-powered internal combustion engine vehicles.

Portable fuel cells can also be used to power small devices such as mobile telephones or personal computers. Larger power generators for recreation and other off-grid applications are under development. For example, Ballard Power Systems has developed the Nexa™ power module, a PEM fuel cell system that generates up to 1200 watts of unregulated direct current electrical power that can be used for industrial and consumer end-product applications. This portable power application is still under development.

Today's emerging hydrogen energy industry is eager to develop hydrogen fuel infrastructure technology that can be used to generate power for stationary, transportation, and portable power applications. Much work needs to be done to reach this goal, but a foundation for future efforts has been established by these various technology sectors.

3. Key Drivers Affecting the Future of Hydrogen Energy Development

The United States' energy sector is experiencing a confluence of events. New technologies are being developed and opportunities for entrepreneurial ideas and innovative approaches are ripening at a time when our capital-intensive, aging energy infrastructure is in need of improvement. Despite this window of opportunity, the overall business environment for energy investments in America today is not conducive to the massive introduction of new technologies.

The Nation faces uncertainties in our energy future and inertia in our infrastructure system.

The Nation faces uncertainties in our energy future and inertia in our infrastructure system. America's energy future will include unpredictable ups and downs, price volatility, regional gluts and shortages, and market instabilities. The natural pace of turnover of existing capital in our infrastructure is relatively slow, there is reluctance to alter traditional systems, and the framework of changing policies and regulations tends to favor incumbent suppliers and technologies.

These factors introduce uncertainties and risk and interfere with making changes. For example, existing inertia in our energy system has made it difficult for policy makers and business executives to make strategic decisions about long-term energy requirements, which has led to delays in decision-making, and has made it hard for businesses to commit to large financial resources to energy investments.

The factors affecting hydrogen's potential are rooted in these issues. Our infrastructure has been designed to provide users with reliable supplies of fossil fuels at an affordable

Summary of Key Drivers Affecting Hydrogen Energy Development

Support	Inhibit	Both Support and Inhibit
■ National security and the need to reduce oil imports ■ Global climate change and the need to reduce greenhouse gas emissions and pollution ■ Global population and economic growth and the need for new clean energy supplies at affordable prices, as hydrogen is potentially available in virtually unlimited quantities ■ Air quality and the need to reduce emissions from vehicles and power plants	■ The inability to build and sustain national consensus on energy policy priorities ■ Lack of a hydrogen infrastructure and the substantial costs of building one ■ Lack of commercially available, low-cost hydrogen production, storage and conversion devices, such as fuel cells ■ Hydrogen safety issues	■ Rapid pace of technological change in hydrogen and competing energy sources and technologies ■ The current availability of relatively low-cost fossil fuels, along with the inevitable depletion of these resources ■ Simultaneous consumer preferences for both a clean environment and affordable energy supplies

cost while protecting the environment. Other forms of energy, including nuclear and renewable sources, may play important roles but face their own hurdles in the global competition for market share.

In developing a vision for the hydrogen economy, certain questions about market and policy forces arise. Are there technological, economic, or policy-related factors, issues, or trends that can encourage a dynamic of change in our current market? If so, how might they affect hydrogen energy development over the next several decades, in terms of supporting or hindering it. Many of these “drivers” will affect not only hydrogen, but also the future of the energy system as a whole.

The tragic events of September 11, 2001, remind every American of the danger of reliance on oil imports from politically unstable countries.

National Security

The need to enhance the supply of domestically produced transportation fuels is great. The tragic events of September 11, 2001, remind every American of the danger of reliance on oil imports from politically unstable countries, some of which have opposing interests to those of the United States. America’s transportation sector relies almost exclusively on refined petroleum products; more than one-half of the petroleum consumed in the United States is imported, and that percentage is expected to rise steadily for the foreseeable future, unless we change our energy use. Hydrogen (along with biofuels) is a versatile energy carrier that could be produced entirely from domestic sources of fossil fuel (e.g., natural gas and coal with capture and sequestration of carbon dioxide), renewable (e.g., solar, wind, and biomass), and nuclear energy, in large quantities. Its use as a major energy carrier would provide the United States with a more diversified energy infrastructure.

Climate Change

The combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions released into the atmosphere. Although international efforts to address global climate change have not yet resulted in policies that all nations have accepted, there is growing recognition that steps to reduce greenhouse gases are needed, and many countries are adopting policies to accomplish that end. Energy and transportation companies, many of which have multi-national operations, are actively evaluating alternative sources of energy.

Hydrogen can play an important role in a low-carbon global economy, as its only byproduct is water. With the capture and sequestration of carbon from fossil fuels, hydrogen is one path for coal, oil, and natural gas to remain viable energy resources, should strong constraints on carbon emissions be required. Hydrogen produced from renewable resources or nuclear energy results in no net carbon emissions.

Population and Economic Growth

Many experts have pointed out that if highly populated countries like China, India, or Indonesia were to adopt energy consumption patterns similar to those of the United States or Europe, world energy supplies would have to increase enormously to meet demand. For example, imagine the energy and environmental consequences of one-half of Chinese households owning automobiles that run on gasoline. That would be about four times the number of car-owning households in the United States today. If these automobiles were to run on hydrogen fuel cells, the environmental consequences and national security issues would be much less.

Many international energy experts are hoping that developing countries will be able to “leap frog” today’s energy devices and infrastructure by adopting advanced technologies. The idea is that as economic growth spreads around the world, developing countries would be able to follow a pattern similar to the one being followed in telecommunications systems: wireless technologies are being installed in certain locations, “leap frogging” the need for telephone lines. Unfortunately, the advanced energy devices that would be needed to “leap frog” current infrastructure, such as hydrogen energy systems and fuel cells, are not yet cost competitive or commercially available on the required economies of scale.

Without such policies, progress toward a hydrogen economy will be severely limited and much slower.

Air Quality

Air quality is a major public health concern. Most of the major metropolitan areas in the United States are in "non-attainment" with the requirements of the Clean Air Act. States are required to develop strategies detailing the steps they plan to take for reaching national ambient air quality goals. California, for example, has been one of the most aggressive states in taking action to reach clean air goals. Personal vehicles and electric power plants are significant contributors to the nation's air quality problems. The introduction of hydrogen-using commercial bus fleets is one of the approaches being taken to achieve compliance with the Clean Air Act.

Consistency in National Energy Policy Priorities

One of the hallmarks of public energy policies in America is their inconsistency from state to state, and the shifts that occur in Federal priorities with each election. The last major piece of Federal energy legislation was the Energy Policy Act, which was enacted in 1992. Since then, there has not been a national consensus on Federal energy policy priorities. For example, prior to the electricity problems experienced in California in 2000 and 2001, electricity restructuring was one of the top national energy priorities. The last three Congresses have held hearings on this subject and there have been Administration electricity legislation proposals, but there has not been a long-term, consistent energy policy.

The United States is missing a sustained national commitment to environmental and energy security goals, and the policies to support them. Hydrogen could provide the basis for such a policy. Since 1990 Congress has authorized funds in support of hydrogen energy research, development, and demonstration. Market-based environmental policies that provide industries with financial reasons to invest in low-emission or carbon-free energy systems could accelerate hydrogen energy development substantially.

The public needs to understand the value of a hydrogen economy in order for businesses to invest in new energy technologies. Public policies need to be developed by government and private entities and put into place to facilitate public acceptance. This in turn would lead to greater market incentives for significant private investment in hydrogen.

For the hydrogen economy to evolve, consumers will need to have convenient access to hydrogen sources.

Hydrogen Infrastructure Costs

As documented in the President's National Energy Policy, America's energy infrastructure is aging and in need of significant upgrades, overhauls, and replacements over the next several decades. This infrastructure includes oil refineries, gas and oil pipelines, power plants, and electricity transmission and distribution facilities such as power lines, transformers, and substations. The capital investment requirements to maintain and improve the infrastructure over the next several decades will total hundreds of billions of dollars.

While hydrogen may be able to use some of the existing infrastructure, specific upgrades and enhancements will be needed to accommodate the unique features of hydrogen, particularly in storage and distribution. The technologies needed to convert the natural gas infrastructure for the use of hydrogen are available today, but are not yet cost-effective. At present there is no motivation to convert to hydrogen, as there are essentially no markets for distributed use of hydrogen energy. Additional infrastructure costs will have to be incurred in the future, when cost-competitive products are available, to enable the transition to the hydrogen economy.

The technical and economic barriers to upgrading the Nation's fueling stations to provide hydrogen represents one of the major stumbling blocks to the expanded use of hydrogen-fueled vehicles. Some automakers estimate that hydrogen would have to be available in at least thirty percent of the nation's fueling stations for a viable hydrogen-based transportation sector to emerge. Private investment in such an infrastructure will not be forthcoming in the absence of supporting and sustained, supportive public policies.

Hydrogen Storage and Conversion Devices

The lack of low-cost and light-weight storage and commercially-available and cost-competitive fuel cells interferes with the development of a hydrogen economy. For the hydrogen economy to evolve, consumers will need to have convenient access to hydrogen, and storage will be one of the keys. Better hydrogen storage systems will enable users to have easy access to hydrogen for vehicles and distributed energy facilities. Hydrogen storage will also enhance the value and potential market share of renewable electricity generation.

Fuel cells are clean, compact, and modular energy generation devices that have the potential to revolutionize the production of electricity and thermal energy, for both stationary and mobile applications. There are several different types of fuel cells; each has advantages and disadvantages. Design and manufacturing breakthroughs are needed to lower costs and enhance reliability and performance. The marketplace will determine which of the several fuel cell options will offer users the most favorable advantages.

Hydrogen internal combustion engine vehicles are being demonstrated and are nearer term than fuel cell vehicles. They offer nearly as many benefits, although they are not strictly zero emissions vehicles.

Concerns About Hydrogen Safety

Perceptions about the safety of hydrogen remain a deterrent to many consumers. The public needs to be aware that safety issues related to hydrogen are being addressed, and perceptions based on misinformation need to be corrected. A public information campaign can help eliminate many of the concerns about hydrogen safety. Effective codes and standards are needed to ensure that these concerns are addressed in equipment designs, manufacturing practices, and operation and maintenance procedures. Appropriate field tests and demonstrations will be needed to increase public confidence and acceptance of hydrogen technologies.

Technological Change

The accomplishments of science over the past century have been astounding. America's energy sector has been a major beneficiary of developments in science and engineering. The electrification of the economy and the ease of personal travel through the use of the automobile are part of the reason why the American economy has become one of the most productive in history.

Examples of the accelerating pace of technological change in recent years are everywhere. There have been many innovations and new product and service offerings in telecommunications, information systems, and biology-based industries. As a result, these have become leading sectors in the United States economy. Development of advanced energy systems, products, and services are also on the horizon. New materials for energy devices such as turbines, engines, and fuel cells are improving rapidly. Advanced concepts in the biological sciences, and in the miniaturization of engineered systems using nanotechnologies, could lead to breakthroughs that revolutionize how energy (including that from hydrogen sources) is produced and used.

Americans demonstrate preferences that both support and hinder the development of clean energy sources.

At the same time, these developments are also affecting conventional fossil, nuclear, and renewable energy systems, which are becoming cleaner, cheaper, and more energy-efficient. For example, recent advances in combined heat and power systems have led to systems that produce electricity and thermal energy at more than double the energy efficiency of the typical power plant, thus reducing emissions, energy costs, and peak electricity demands.

Availability of Fossil Energy Resources

Affordable coal, oil, and natural gas supplies are available around the world. Analysts warn, however, that world oil production cannot be sustained at current levels indefinitely and that the development of America's natural gas resources, while extensive, are not inexhaustible. Coal is the major fuel for electricity production in America. Clean coal technologies improve efficiency and reduce emissions. Fossil fuels are expected to be America's fuels of choice for the foreseeable future.

If demand for fossil fuels continues to increase, resource constraints will push fossil fuel prices up over the next several decades (energy analysts differ as to how much and when). This will spur the development of non-fossil alternatives such as solar, wind, geothermal, biomass, and nuclear, and fossil alternatives that sequester the carbon dioxide, and encourage the transition to hydrogen. In the meantime, the current availability and relatively low cost of fossil fuels moderate the pace of development of alternative sources of energy.

Consumer Preferences

Americans demonstrate preferences that both support and hinder the development of clean energy sources. The typical consumer has grown increasingly aware of the environmental, health, and safety consequences of energy. This, in combination with legislation, has contributed to the growth in demand for environmentally friendly products and services such as energy efficient appliances and equipment, renewable energy, and "green power" offerings from local utilities. In many non-attainment areas, for example, environmental requirements to reduce emissions receive public support, even when they result in higher fuel taxes or inconvenience in commuting.

There are also other energy consumer trends that require high-value services that command premium prices. For example, extra high reliable electric service is required by a growing number of businesses relying on digital equipment, such as computers, or operating 24 hours a day, seven days a week. Protection against energy price volatility is another possible high-value service. These premium markets, like distributed energy and power parks, provide growing opportunities for hydrogen energy, especially early in the transition.

In contrast, public support for low energy prices is strong. Americans enjoy gasoline prices that are among the lowest in the world. Consumers rank fuel economy relatively low on the list of desired attributes for automobiles. The ten-year period from 1992 to 2001, the longest era of sustained economic growth in American history, coincided with a period of historically low energy prices. Many Americans are quick to contrast that era with the ten-year period from 1972 to 1981—an era marked by relatively low economic growth, high inflation and unemployment, and high energy prices.

Summary

There are several key drivers that will likely affect hydrogen energy development. Concerns regarding national security, global climate change, and worldwide population and economic growth will increasingly promote systems that support hydrogen development. The lack of a national consensus on energy policy priorities, a hydrogen infrastructure, commercially viable hydrogen technologies, and the public perception of hydrogen safety issues have the potential to inhibit hydrogen energy development. Drivers that could both support and inhibit the development of hydrogen are the rapid pace of technological change in energy technologies, the current availability of low cost fossil fuels and their eventual depletion, and mixed consumer preferences for clean and cheap energy.

4. A National Vision of the U.S. Hydrogen Economy

Vision: Hydrogen is America's clean energy choice. It is flexible, affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country.

At the time this vision is realized, hydrogen produced from fossil fuels (with carbon capture and sequestration), renewable energy, and nuclear energy will be used throughout the transportatiion and electric power sectors. Hydrogen will be produced in centralized facilities in remote locations, in power parks and fueling stations in our communities, in distributed facilities in rural areas, and onsite at customers' premises. Today we have a hydrocarbon economy. Tomorrow we will have weaned ourselves from carbon and will live in a "hydrogen economy." In the hydrogen economy...

> *America will enjoy a secure, clean, and prosperous energy sector that will continue for generations to come. American consumers will have access to hydrogen energy to the same extent that they have access to gasoline, natural gas, and electricity today. It will be produced cleanly, with near-zero net carbon emissions, and it will be transported and used safely. It will be the "fuel of choice" for American businesses and consumers. America's hydrogen energy industries will be the world's leaders in hydrogen-related equipment, products, and services.*

One major foundation for this vision is the development of an energy infrastructure that can support the expanded production, delivery, storage, and use of hydrogen energy. A hydrogen infrastructure is likely to develop on a regional level, since it can be made from a variety of feedstocks, and will resemble the electricity grid more than the current oil delivery system. Construction of this infrastructure will take time and will require significant resources. As a result, the hydrogen economy will evolve over the next several decades. Hydrogen storage weight and volume reductions, mass production of fuel cells, construction of the necessary infrastructure, and expanded use of portable and distributed power generation devices will sustain the momentum towards a hydrogen economy. Infrastructure will begin with pilot projects and expand to local, regional, and ultimately national and international applications.

A strong public-private partnership will be a key feature of this evolutionary process. Together, government and private organizations will facilitate appropriate research, development, and demonstration programs; educate the public; and develop codes and standards. Mounting public pressures for a cleaner environment, and for more secure sources of energy supplies, will lead to more stringent policies for reducing air emissions and limiting oil imports.

With steady progress and a few significant technology breakthroughs, the Nation will make a committed switch to a hydrogen economy—over the next several decades a confluence of events will mark a steep increase in hydrogen energy development. By that time, hydrogen production costs will be lower, the basic components of a national hydrogen storage and distribution network will be in place, and hydrogen-powered fuel

Icelandic New Energy Ltd., a joint venture company endorsed by Iceland's government, was formed in 2000 to work towards a hydrogen economy. It leads new projects that facilitate the use of hydrogen as an alternative fuel to reduce greenhouse gas emissions, increase energy efficiency, and protect depleting natural resources. Icelandic New Energy plans to gradually switch the nation's vehicles—first buses, then cars, then fishing vessels—to hydrogen power. The company expects to have three hydrogen-powered buses running in Reykjavik by the end of 2002, fuel cell-powered passenger cars available in 2003 to 2004, and a demonstration of a fuel cell boat in 2006.

cells, engines, and turbines will be mature technologies that are mass produced for use in cars, homes, offices, and factories.

Early glimpses of this vision can already be seen in pilot programs that are underway in a few U.S. locations and several other countries; Iceland is a notable example. There are many advantages in partnering with other countries in the development of new technologies for the "hydrogen economy."

Future Hydrogen Production Processes

At the time the vision for a hydrogen economy becomes a reality, several decades from now, hydrogen will still be produced from fossil fuels, but also from biomass and water using thermal, electric, and photolytic processes.

Hydrogen produced from water will be a cost competitive alternative to hydrogen made from hydrocarbons. Some techniques will include inexpensive electrolyzers that use solar, geothermal, wind, or nuclear power; photochemical or photoelectrochemical devices; and biological systems such as algae. Very low cost electricity will be needed for cost-competitiveness, such as off-peak power at one to two cents per kilowatt hour, and the amount of hydrogen produced in this manner will be limited in comparison to future demands for fuel. Electrolysis could make locally important contributions where low cost power is available, although the overall contribution to a full scale hydrogen economy will depend on the relative costs.

Sources of Hydrogen

Conversion Process (Today → Future); Sources ↓

	Thermal	Electric	Photolytic
Fossil Fuels	✓		
Biomass	✓		✓
Water		✓	✓

The Nation will have a combination of central station and distributed hydrogen production facilities; the mix will depend on local economics and regional resource endowments. Central station facilities will consist of multi-product refineries that use fossil fuels or biomass as feedstocks, and that provide hydrogen, electricity, thermal energy, chemicals, and other industrial products. One can also envision central station nuclear, solar, wind, or geothermal facilities for the production of hydrogen by splitting water. Those facilities that use fossil fuels and biomass as feedstocks will have carbon capture and sequestration capabilities. Distributed production of hydrogen will occur on-site (at homes, offices, factories, and onboard vehicles) or at the community level at places such as fueling stations or power parks.

Future Infrastructure

A national network will be in place to provide hydrogen to users in every region, state, and locality. The network will evolve from the existing fossil fuel-based infrastructure and will accommodate both centralized and decentralized production facilities. Pipelines will be the preferred choice for distributing hydrogen to high-demand areas. Trucks and rail will be used to distribute hydrogen to rural and other lower-demand areas. On-site hydrogen production and distribution facilities will be available where demand is high enough to sustain maintenance of the technologies.

Future Storage Devices

A selection of relatively lightweight, low cost, and low volume hydrogen storage devices will be available to meet a variety of 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 mature technologies in mass production. Storage devices based on carbon structures will be under development.

Future Conversion Technologies

Fuel cells will be mass-produced and will be cost-competitive and mature technologies. Advanced hydrogen-powered energy generation devices such as combustion turbines and reciprocating engines will be in widespread commercial use.

Future End-Use Energy Markets

Hydrogen will be available for every end-use energy need in the economy, including transportation, power generation, and portable power systems. Hydrogen will be the dominant fuel for government and commercial vehicle fleets. It will be used in a large number of personal vehicles and light duty trucks. It will be combusted directly and mixed with natural gas in turbines and reciprocating engines for electricity and thermal energy in 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.

SunLine Transit Agency opened a hydrogen generation, storage, and fueling facility in April 2000 in Thousand Palms, California, with the help of industry and government partners. SunLine uses electrolyzers to generate hydrogen from renewable energy (photovoltaics) and a reformer to generate it from natural gas. The agency stores hydrogen in a 16-tube storage trailer that is attached to a cascade control panel used to fill hydrogen buses and pickup trucks at a public fueling island. SunLine plans to add another electrolyzer, expanded storage, a wind-generated fuel cell demonstration project, and increased dispensing pressure to its “Clean Fuels Mall” in the near future.

This chapter presented a vision of the hydrogen economy. The following chapter discusses in further detail how the United States can transition to a hydrogen economy through public-private partnerships.

5. Transition to the Hydrogen Economy

There are certain achievements to be made and pitfalls to avoid in the transition to a hydrogen economy. Rather than offering predictions or specific prescriptions, the following section discusses various goals and hazards and outlines plausible scenarios.

Phase One – *Progress in Technologies, Policies, and Markets*

Significant laboratory progress is expected in the first transition phase in the form of research and demonstration that supports industry's pre-commercial efforts. Carmakers will test several types of hydrogen-using prototypes. Research will focus on bringing down the cost of fuel cells and developing solid-state storage devices, primarily using metal hydrides, but also exploring carbon structures (such as nanotubes and fullerenes) and glass microspheres.

The transition to the hydrogen economy has already begun. We are a hydrocarbon economy today. We have yet to learn how to inexpensively extract and convert hydrogen from hydrocarbon (or other) sources without releasing harmful by-products into the environment. But we are quickly learning....

Natural gas steam reforming will continue to be the primary means for producing hydrogen. While progress will be made in developing advanced hydrogen production technologies, market readiness will not yet be achieved.

Hydrogen use in internal combustion engines will build support for infrastructure development. Testing of fuel cell buses and cars and of hydrogen-fueled internal combustion engines will likely continue to expand, particularly in non-attainment areas. Industry markets for proton exchange membrane fuel cells for stationary applications will be further developed, and auto companies will begin to build hydrogen fuel cell cars in quantity. Tests of fuel cells for combined heat and power applications in buildings will increase, and development of hydrogen fuel cells for portable power devices will continue.

The first phase will also include the creation of hydrogen-related policies on energy and the environment, including the reduction of energy imports, managing greenhouse gas emissions, and strengthening the control of air pollution. International standards for the safe use of hydrogen will be implemented around the world. The restructuring of electricity and natural gas markets in the United States will be completed, thus expanding the prospects for the installation of distributed energy systems. Government will address liability, permitting, and codes and standards in order to provide a framework for commercial development to proceed.

Phase Two – *Transitioning to the Marketplace*

Many significant technology developments will have to occur in the next phase in order for the hydrogen economy to develop. The most necessary breakthrough will have to be cost reductions of fuel cells through the development of large-scale manufacturing capabilities for stationary and mobile units. The initial stages of a hydrogen delivery system will have to be in place.

Specifically, significant advances will have to be made to lower the cost of hydrogen production and storage. Natural gas reforming will remain the primary source of hydrogen production. Coal gasification and the use of nuclear and renewable technologies will be used more heavily. Lighter-weight and lower-cost storage devices will become commercially available.

Power parks and fueling stations will include distributed hydrogen production systems, some of which will be renewable (e.g., solar and wind). A few will use photobiological and photoelectrochemical techniques. Hybrid hydrogen internal combustion engines will be further developed and more widely used.

Federal and state government facilities will play an increasingly expanded role in moving hydrogen technologies into the marketplace. Many will have served as "first use" sites for hydrogen energy systems, such as municipal bus services. Urban emergency services, fire, and police facilities will also use distributed energy devices to ensure continuous power, and some will certainly opt for hydrogen-based systems because of the environmental advantages. Military applications of hydrogen energy systems (e.g., in vehicles, ships, and aircraft) will be demonstrated, and there will be numerous instances of hydrogen fuel cells providing combined heat and power services for buildings.

Phase Three – *Expansion of Markets and Infrastructure*

This is the phase in which technology advancements in hydrogen extraction will reduce costs and expand market share.

The market will be penetrated with the widespread use of fuel cell-powered buses and government vehicles. Emphasis will be placed on expanding from local pockets of hydrogen energy development to building a national hydrogen infrastructure. Although hydrogen production will often occur onsite or onboard, it will also be produced in large-scale refineries that will use coal or biomass as a feedstock for the simultaneous production of hydrogen, electricity, thermal energy, chemicals, and other fuels.

Large- and small-scale hydrogen storage using hydrides will become mature technologies and enter mass production. Other advanced storage techniques such as carbon structures will be in the development stage but close to commercialization. National policies will support hydrogen market expansion, and state and local standards will be in place. Siting and permitting of hydrogen technologies will be more streamlined. State and local governments will play a major role in this phase.

Phase Four – *Realization of the Hydrogen Vision*

Eventually hydrogen will overtake fossil fuels for most end-use energy market applications. Economical and environmentally friendly means will be found for extracting hydrogen from fossil fuels, biomass, and water. Hydrogen "farms" that use biological systems such as algae to extract hydrogen from water will be in use. Gasification plants will extract hydrogen from coal and biomass. Carbon capture will limit emissions, and new industrial uses will put captured carbon to work for industrial feed stocks, building materials, and other applications.

A national infrastructure that supports the use of hydrogen for fuel and electricity production will be in place. United States companies that spent decades developing hydrogen technologies will be exporting products and services around the world. American consumers will be enjoying the economic benefits of a financially sound hydrogen energy sector and the environmental benefits of clean energy systems.

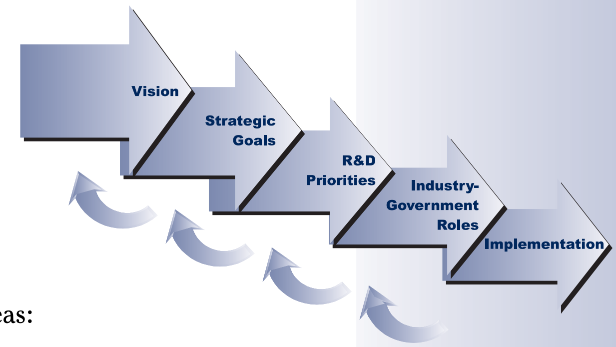
The market for hydrogen vehicles as personal transportation will expand as a natural outgrowth of technology, market, and policy development. There will be no need for government mandates. The practice of using hydrogen vehicles to provide heat and power for the workplace during the day, and homes during the night, will be commonplace. The line between the transportation sector and the power system will blur. The hydrogen economy will become reality.

6. A Path Forward

If significant progress toward a hydrogen economy is to occur, a new public-private partnership needs to form and spring into action immediately. The ultimate vision for the hydrogen economy is decades in the future and the amount of research, development, public education, institution building, and infrastructure construction needed to get there is enormous.

A useful venue for building this new public-private partnership is the joint development of a *National Hydrogen Energy Roadmap*. The roadmapping process can provide industry practitioners, government officials, and technologists from universities and the National Laboratories with the opportunity to collectively identify near-, mid-, and long-term actions. The process can be used to set priorities for research, development, and demonstration programs, and it can outline the relative roles of industry, government, universities, National Laboratories, and non-governmental organizations.

Planning Logic of the Typical Vision and Roadmap Process



This roadmap process will need to address a number of areas:

- Technologies for hydrogen production
- Technologies for hydrogen delivery and transportation
- Technologies for hydrogen storage
- Technologies for hydrogen conversion
- Scope and directions for public-private partnerships, both nationally and internationally
- Codes and standards for safe production, delivery, and use of hydrogen
- Education of the general public and government and private decision makers about the potential benefits from the expanded use of hydrogen
- End-use energy markets for hydrogen including the potential for "first use" fleet applications in Federal facilities, vehicles, and equipment

Participants in the roadmap process should include technical experts and industry practitioners from domestic and international organizations, as they have the requisite capabilities and experience to chart the critical hydrogen energy development pathways over the next several decades.

Examples of possible roadmap participants are listed in the table below.

Roadmap Areas	Roadmap Participants
Technology development	Industry, universities, National Laboratories
Market applications	Equipment manufacturers, industrial end users, building owners and operators, and Federal energy managers
Public education	Federal, State, and local governments; school districts; universities; media companies
Codes and standards	State and local governments, professional associations, standards organizations

The roadmap needs to be systematic from resource to end-use. Interfaces matter. For example, it may not be best to have refueling stations at one pressure and onboard storage tanks at another.

Working together, industry, universities, and government can help America realize the hydrogen vision. This entails building on our existing energy infrastructure and current hydrogen energy technologies to meet mutually set milestones. Public and private entities can cooperate to overcome hurdles and develop technologies and policies that fit America's drive for clean, affordable, secure, and efficient energy systems.

Appendix: Participating Organizations

Air Products and Chemicals, Inc., Arthur Katsaros

Alameda Contra Costa Transit, Jaimie Levin

Avista Labs, Inc., J. Michael Davis

Ballard Power Systems, Stephen Kukucha

Battelle-Pacific Northwest National Laboratory, Jae Edmonds

BP, Lauren Segal

California Energy Commission, Susan Brown and Louise Dunlap

DaimlerChrysler, William Craven

DCH Technology, Inc., John Donohue

Energetics, Inc., Rich Scheer, Jack Eisenhauer, Ross Brindle (Facilitators)

Entergy Nuclear, Inc., Dan Keuter

ExxonMobil Refining & Supply Company, William Lewis

Ford Motor Company, Frank Balog

GE Corporate Research & Development, Sanjay Correa

General Motors, Byron McCormick

Hawaii Natural Energy Institute, Richard Rocheleau

House Committee on Science, John Darnell

Kennedy Space Center, David Bartine

Millennium Cell, Stephen Tang

National Academy of Sciences, James Zucchetto

National Energy Technology Laboratory, Rita Bajura

National Governors Association, Ethan Brown

National Renewable Energy Laboratory, Richard Truly

Natural Resources Defense Council, Daniel Lashof

NiSource Inc., Arthur Smith

Office of Assistant Secretary of the Navy (I&E), Leo Grassilli

Office of Naval Research, Richard Carlin

Office of Senator Akaka, Jaffer Mohiuddin

Praxair, Inc., Donald Terry

Princeton University, Joan Ogden

Proton Energy Systems, Inc., William Smith

Quantum Technologies, Alan Niedzwiecki

Stuart Energy Systems, Andrew T.B. Stuart

SunLine Transit Agency, Richard Cromwell

Texaco Energy Systems, Graham Batcheler

The Wexler Group, Robert Walker

U.S. Department of Energy, Robert Card, Robert Dixon, David Garman, Tom Gross, R. Shane Johnson, Karen Kimball, Robert Kripowicz, Richard Moorer, William Parks, Frank Wilkins

U.S. House of Representatives, Congressman Roscoe Bartlett

UTC Fuel Cells, William Miller

Verizon, Thomas Bean

World Resources Institute, James MacKenzie

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