

Toward a More Secure and
Cleaner Energy Future for America



NATIONAL HYDROGEN ENERGY ROADMAP

PRODUCTION • DELIVERY • STORAGE • CONVERSION
• APPLICATIONS • PUBLIC EDUCATION AND OUTREACH

Based on the results of the
National Hydrogen Energy Roadmap Workshop
Washington, DC
April 2-3, 2002

November 2002



United States Department of Energy

As we act on President Bush's National Energy Policy, we are focusing on next-generation technologies that expand the diversity of America's supply of energy and "leap frog" the status quo. This requires a revolution in how we find, produce, deliver, store, and use energy.

Hydrogen represents a potential solution to America's needs.

To talk about "the hydrogen economy" is to talk about a world that is fundamentally different from the one we know now.

A hydrogen economy will mean a world where our pollution problems are solved and where our need for abundant and affordable energy is secure...and where concerns about dwindling resources are a thing of the past.

At the Department of Energy, we're not just talking about the hydrogen economy. We're working to make it a reality.

This Roadmap provides a framework that can make a hydrogen economy a reality.

Spencer Abraham
Secretary of Energy

A Plan for Action

Hydrogen holds the potential to provide a clean, reliable, and affordable energy supply that can enhance America's economy, environment, and security. This Roadmap provides a blueprint for the coordinated, long-term, public and private efforts required for hydrogen energy development.

In the coming decades, the United States will need new energy supplies and an upgraded energy infrastructure to meet growing demands for electric power and transportation fuels. Hydrogen provides high efficiency, can be produced from a variety of domestically available resources, and offers near-zero emissions of pollutants and greenhouse gases. Developing hydrogen as a major energy carrier, however, will require solutions to many challenges in the areas of infrastructure, technology, and economics.

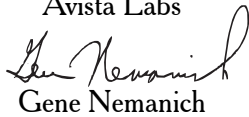
The U.S. Department of Energy initiated a National Hydrogen Vision and Roadmap process in response to recommendations in the *National Energy Policy*. The first step in that process resulted in publication of the *National Vision of America's Transition to a Hydrogen Economy* (February 2002).¹ This Roadmap represents the next step in that process.

This Roadmap is neither a government research and development plan nor an industrial commercialization plan. Rather, it explores the wide range of activities required to realize hydrogen's potential in solving U.S. energy security, diversity, and environmental needs. It is intended to inspire the organizations that invest in hydrogen energy systems—public and private, State and Federal, businesses and interest groups—to become involved in a coordinated effort to reduce risk, improve performance, decrease cost, and implement a secure, clean, and reliable energy future.

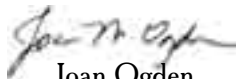
Meeting the challenges associated with the development of a hydrogen economy will demand considerable time and resources. Activities to progress toward that goal need to begin now.



Mike Davis
Avista Labs



Gene Nemanich
Chevron Texaco Technology Ventures



Joan Ogden
Princeton University



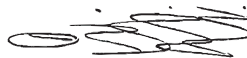
Jeff Serfass
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Art Katsaros
Air Products & Chemicals, Inc.



Alan Niedzwiecki
Quantum Technologies

The primary challenge to using more hydrogen in our energy systems is the cost of producing, storing, and transporting it.

— National Energy Policy, 2001

¹ The Vision document can be downloaded from www.eren.doe.gov/hydrogen.

Executive Summary

An energy economy based on hydrogen could resolve growing concerns about America's energy supply, security, air pollution, and greenhouse gas emissions. Hydrogen offers the long-term potential for an energy system that produces near-zero emissions and is based on domestically available resources. Before hydrogen can achieve its promise, however, stakeholders must work together to overcome an array of technical, economic, and institutional challenges.

Hydrogen has the potential to play a major role in America's future energy system. This Roadmap outlines key issues and challenges in hydrogen energy development and suggests paths that government and industry can take to expand use of hydrogen-based energy.

MAJOR FINDINGS AND CONCLUSIONS

Widespread use of hydrogen will affect every aspect of the U.S. energy system, from production through end-use. The individual segments of a hydrogen energy system—production, delivery, storage, conversion, and end-use applications—are closely interrelated and interdependent. Design and implementation of a hydrogen economy must carefully consider each of these segments as well as the “whole system.”

Production—Government-industry coordination on hydrogen production systems is required to lower overall costs, improve efficiency, and reduce the cost of carbon sequestration. 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” (demand/supply) 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).

This Roadmap outlines key issues and challenges in hydrogen energy development and suggests paths that government and industry can take to expand use of hydrogen-based energy.

Ultimately, consumer preferences drive the choices made in energy markets, technology development, and public policy.

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.

All individual segments of the hydrogen industry as well as the overall hydrogen energy system must address several cross-cutting challenges. These challenges include insuring safety, building government/industry partnerships for technology demonstration and commercialization, coordinating activities by diverse stakeholders, maintaining a strong research and development program in both fundamental science and technology development, and implementing effective public policies. Two additional cross-cutting areas could become powerful drivers to assist in addressing these challenges: customer education and the development of codes and standards.

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. 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.

Development of hydrogen energy technologies represents a potential long-term energy solution for America. A coordinated and focused effort is necessary to bring public and private resources to bear on evaluating the costs and benefits of the transition to a hydrogen economy. Next steps will include the development of detailed research and development plans for each of the technology areas listed above. A significant commitment and coordination of resources will be essential to the success of this effort.

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1 Introduction

Expanded use of hydrogen as an energy carrier for America could help address concerns about energy security, global climate change, and air quality. Hydrogen can be derived from a variety of domestically available primary sources, including fossil fuels, renewables, and nuclear power. Another key benefit is that the by-products of conversion are generally benign for human health and the environment.

Despite these compelling benefits, realization of a hydrogen economy faces multiple challenges. Unlike gasoline and natural gas, hydrogen has no existing, large-scale supporting infrastructure—and building one will require major investment. Although hydrogen production, storage, and delivery technologies are currently in commercial use by the chemical and refining industries, existing hydrogen storage and conversion technologies are still too costly for widespread use in energy applications. Finally, existing energy policies do not promote consideration of the external environmental and security costs of energy that would encourage wider use of hydrogen. Table 1 (below) summarizes the key drivers that support and inhibit the development of hydrogen energy.

Developing hydrogen as a realistic energy option will necessitate an unprecedented level of sustained and coordinated activities by diverse stakeholders. Recognizing the need to develop a coordinated national agenda, the U.S. Department of Energy initiated a National Hydrogen Vision and Roadmap process to incorporate the opinions and viewpoints of a broad cross-section of those stakeholders. The process involved two key meetings: the National Hydrogen Vision Meeting and the National Hydrogen Energy Roadmap Workshop.

Summary of Key Drivers Affecting Hydrogen Energy Development

Support	Inhibit	Both Support and Inhibit
<ul style="list-style-type: none"> ■ National security and the need to reduce oil imports ■ Global climate change and the need to reduce and ultimately stabilize greenhouse gas emissions and pollution ■ Global population and economic growth ■ The need for new, clean energy supplies at affordable prices ■ Air quality and the need to reduce emissions from vehicles and power plants 	<ul style="list-style-type: none"> ■ The difficulties in building and sustaining national consensus on long term energy policy priorities ■ Lack of a hydrogen infrastructure and the substantial costs of building one ■ Lack of commercially available, low-cost hydrogen production², storage, and conversion devices ■ Hydrogen safety issues ■ The need for additional demonstrations of carbon sequestration and lower-cost sequestration methods 	<ul style="list-style-type: none"> ■ Rapid pace of technology developments supporting hydrogen and competing energy carriers ■ The current availability of relatively low-cost fossil fuels exacerbating the inevitable depletion of these resources ■ Simultaneous consumer preferences for both a clean environment and affordable energy supplies

² While large quantities of hydrogen are currently produced at reasonable cost by steam reformation of methane, this source relies on a limited fossil resource (natural gas) and releases greenhouse gas (CO₂)

NATIONAL HYDROGEN VISION MEETING

The National Hydrogen Vision Meeting was held on November 15-16, 2001, in Washington, DC. Participants included more than 50 business executives and public policy leaders from Federal and State agencies, the U.S. Congress, and environmental organizations. The U.S. Department of Energy initiated the meeting in response to recommendations in the National Energy Policy regarding hydrogen technologies. The aims of the meeting were to identify a common vision for the hydrogen economy, the time frame in which such a vision could be expected to occur, and the key milestones for achieving it.³

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.

Major findings from the vision meeting include the following:

- Hydrogen energy could play an increasingly important role in America's energy future, as it has the potential to help reduce dependence on petroleum imports and lower pollution and greenhouse gas emissions.
- The transition to a hydrogen economy has begun, and could take several decades to achieve.
- The development of hydrogen technologies needs to be accelerated.
- There are "chicken-and-egg" issues regarding market segment development and how supply and demand will push or pull these activities.

Participants at the meeting drew the following conclusions about the vision:

- Federal and State governments will need to implement and sustain consistent energy policies that elevate hydrogen as a priority.
- Strong public-private partnerships will need to focus on finding new ways to collaborate on the development and use of hydrogen energy.
- A logical next step will be the development of a *National Hydrogen Energy Roadmap*, which will need to address research, development, testing, outreach, and codes and standards related to the production, delivery, storage, and use of hydrogen.

The vision document, "*A National Vision of America's Transition to a Hydrogen Economy – To 2030 and Beyond*" outlines the characteristics of a hydrogen economy, explains that the full transition process could take several decades, and describes the potential benefits that a successful transition will produce.⁴

³ Proceedings from the meeting can be downloaded from www.eren.doe.gov/hydrogen.

⁴ The Vision document can be downloaded from www.eren.doe.gov/hydrogen.

NATIONAL HYDROGEN ENERGY ROADMAP WORKSHOP

The National Hydrogen Energy Roadmap Workshop took place on April 2–3, 2002, in Washington, D.C.⁵ Approximately 220 technical experts and industry practitioners from public and private organizations participated in the meeting (a list of participating organizations is located in the Appendix). Seven leaders from industry and academia with expertise in hydrogen systems helped guide the subsequent roadmap development process.

During the workshop, participants divided into breakout groups based on the roadmap segments. They discussed key needs that should be addressed in order to achieve the Vision; appropriate roles for industry, government, universities, and National Laboratories; development of public-private partnerships; and time frames for the activities.

Roadmap Leaders

Leader	Affiliation	Roadmap Segment
Frank Balog	Ford Motor Company	Applications
Mike Davis	Avista Labs	Energy Conversion
Art Katsaros	Air Products & Chemicals, Inc.	Delivery
Gene Nemanich	ChevronTexaco Technology Ventures	Production
Alan Niedzwiecki	Quantum Technologies	Storage
Joan Ogden	Princeton University	Systems Integration
Jeff Serfass	National Hydrogen Association	Public Education & Outreach



Roadmap leaders participated in a panel discussion during the opening plenary session of the Hydrogen Energy Roadmap Workshop on April 2, 2002. Panelists included (from left to right) Mike Davis, Art Katsaros, Frank Balog, Alan Niedzwiecki, Gene Nemanich, Jeff Serfass, and Joan Ogden.

This Roadmap is a product of the workshop. It is intended to help identify the strategic goals, barriers, and key activities required to evaluate the costs and benefits of a hydrogen economy and to lay a foundation for the public-private partnerships needed to implement the plan. It has been prepared in conjunction with a parallel effort by the U.S.

Department of Energy to report to Congress on “...the technical and economic barriers to the commercial use of fuel cells in transportation, portable power, and stationary and distributed power applications by 2012”. The fuel cell report and hydrogen energy roadmap are complementary activities.⁶

The following chapters reflect the ideas and priorities put forth by the workshop participants. Each chapter is focused on an industry segment and provides a description of current status, challenges to achieving the vision, and paths forward.

⁵ A proceedings from the meeting can be downloaded from www.eren.doe.gov/hydrogen.

⁶ The U.S. Department of Energy *Fuel Cell Report to Congress—Interim Assessment*, April 2002, can be downloaded from www.eren.doe.gov/hydrogen.

2 Systems Integration

Effective design and implementation of a hydrogen-based energy system requires a “whole system” approach. Complex dependencies among the diverse system components dictate that cross-cutting, system-level issues and concerns receive close attention.

A number of cross-cutting issues will influence hydrogen production, storage, delivery, conversion, applications, education, and outreach:

- Development of national and international codes and standards for hydrogen use (see box on the next page)
- Safety precautions
- Consumer acceptance—providing the expected performance at a reasonable cost
- Collaborative research and development
- Technology validation through demonstrations by government/industry partnerships (The government has a role as an early adopter of integrated hydrogen supply and end-use technologies and as a developer of the hydrogen infrastructure.)
- Systems analyses to explore various pathways to widespread hydrogen energy use, including full cost accounting for all competing energy systems
- Ready accessibility to existing information on hydrogen technologies

System integration addresses ways in which different parts of a system work together from technical, economic, and societal standpoints. In many cases, system optimization may require a distinctly different approach from the optimization of a single part. Similarly, a systems focus makes it easier to identify key technical or market barriers in any one part of the system that might impede the development of the whole.

Optimization at the system level will require the following:

- Coordination of technology development between hydrogen producers and end-users (who require hydrogen at a particular purity and pressure)
- A strong, coordinated, and focused research and development program—breakthroughs in hydrogen storage, production, and use could influence how fast and in what way(s) a hydrogen economy develops
- Efficient coordination of supply and demand to solve the perceived “chicken and egg” problem in transportation markets—vehicle manufacturers wish to be assured of fuel supply, while suppliers wish to be assured of a market

Finally, moving to widespread use of hydrogen as an energy carrier involves profound changes in how we view and use energy as individuals and as a society. Actions in the following areas are essential to establishing the underlying set of “system level” pre-conditions or the context for creating a hydrogen energy system:

- Government leadership to identify and sustain the required long-term activities
- Adoption of policies that consistently incorporate the external costs of energy (such as energy supply security, air quality, and global climate change) and provide a clear signal to industry and consumers
- Development of domestic and international markets for hydrogen energy to harness the projected growth of energy demand in developing nations over the next half century

The ensuing chapters elaborate upon these issues.

Codes and Standards

Impact on Technology Acceptance and Commercialization

Applicable codes and standards are an important enabler for the commercialization of any new technology or product. Although industry uses hydrogen extensively as a chemical, hydrogen use in consumer products will require a completely separate set of codes and standards. The Hydrogen Codes and Standards Coordinating Committee was established to coordinate the diverse activities by the large number of organizations and activities involved in developing and adopting codes for hydrogen technologies. The committee communicates across the hydrogen community and works for the development of consistent codes and standards to accelerate the commercialization of fuel cell and hydrogen technologies.

Codes. The path by which new technologies gain approval elucidates the importance of codes. When codes do not specifically and prescriptively address new technologies (or products, designs, or materials), regulatory authorities rely on information provided by the designer, technology purveyor, or testing entity to validate that the proposed technology/design meets the intent of the code—including all safety requirements. Regulatory authorities unfamiliar with a new product may request substantial documentation, which can drastically delay approvals and could affect competitive positions in the market. To facilitate the introduction of hydrogen as an energy carrier, code officials, industry, and National Laboratories have been working over the past three years to draft new model codes that specifically cover emerging hydrogen technologies for consideration by the various code-enforcing jurisdictions.

The International Code Council is in the process of adopting a new edition of its family of model national uniform building codes. Previous editions of these model codes did not address hydrogen as an energy carrier, nor did they address fuel cells as generating devices or appliances. To remedy these omissions, an Ad Hoc Committee on hydrogen technologies was formed to develop and propose amendments to the codes. Adoption of the proposed amendments by the International Code Council will greatly reduce the time required to include hydrogen technologies in local building codes. Similar efforts are underway with the National Fire Protection Association, which is also in the process of adopting model building codes. Technical experts from industry, universities, and National Laboratories are working with the National Fire Protection Association to ensure that its model codes for hydrogen technologies are consistent with those of the International Code Council.

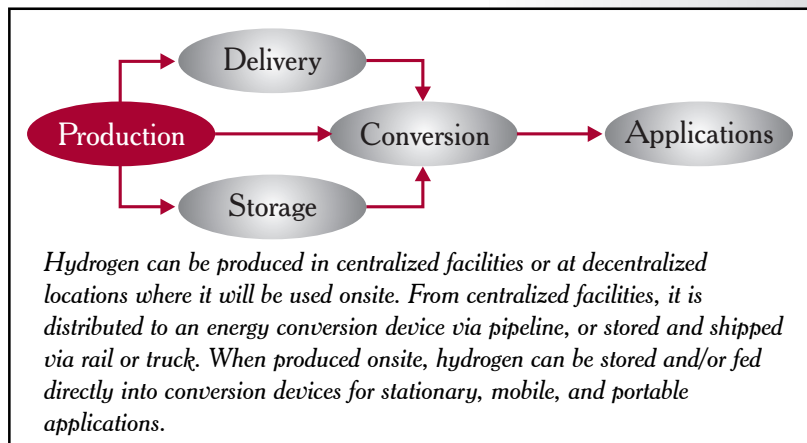
Standards. The International Standards Organization Technical Committee 197 has also been working to adopt international standards for hydrogen technologies. This international forum has succeeded in getting four standards adopted under the International Standards Organization process, which will be essential in achieving harmonious global standards and regulations for hydrogen applications. Ongoing efforts to establish standards are focusing on establishing safe handling practices, facilitating standard interfaces, eliminating barriers to international trade, and developing quality criteria and testing methods.

3 Production

INTRODUCTION

Hydrogen can be produced from a variety of sources, including fossil fuels; renewable sources such as wind, solar, or biomass; nuclear or solar heat-powered thermochemical reactions; and solar photolysis or biological methods.

Hydrogen production today: The United States hydrogen industry currently produces nine million tons of hydrogen per year for use in chemicals production, petroleum refining, metals treating, and electrical applications. Hydrogen is primarily used as a feedstock, intermediate chemical, or, on a much smaller scale, a specialty chemical. Only a small portion of the hydrogen produced today is used as an energy carrier, most notably by the National Aeronautics and Space Administration.



Although hydrogen is the most abundant element in the universe, it does not naturally exist in large quantities or high concentrations on Earth—it must be produced from other compounds such as water, biomass, or fossil fuels. Various methods of production have unique needs in terms of energy sources (e.g., heat, light, electricity) and generate unique by-products or emissions.

Steam methane reforming accounts for 95 percent of the hydrogen produced in the United States. This is a catalytic process that involves reacting natural gas or other light hydrocarbons with steam to produce a mixture of hydrogen and carbon dioxide. The mixture is then separated to produce high-purity hydrogen. This method is the most energy-efficient commercialized technology currently available, and is most cost-effective when applied to large, constant loads.

Partial oxidation of fossil fuels in large gasifiers is another method of thermal hydrogen production. It involves the reaction of a 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 natural gas, heavy oils, solid biomass, and coal. Its primary by-product is carbon dioxide.

How much is 9 million tons of hydrogen per year?

Enough to fuel 20 to 30 million hydrogen fueled cars, or enough to power 5 to 8 million homes.

Hydrogen can also be produced by using electricity in electrolyzers to extract hydrogen from water. Currently this method is not as efficient or cost effective as using fossil fuels in steam methane reforming and partial oxidation, but it would allow for more distributed hydrogen generation and open possibilities for using electricity made from renewable

and nuclear resources. The primary by-products are oxygen from the electrolyzer and carbon dioxide from electricity generation.

With most hydrogen now being produced from hydrocarbons, the cost per unit of energy delivered through hydrogen is higher than the cost of the same unit of energy from the hydrocarbon itself.

Other methods hold the promise of producing hydrogen without carbon dioxide emissions, but all of these are still in early development phases. They include thermochemical water-splitting using nuclear and solar heat, photolytic (solar) processes using solid state techniques (photoelectrochemical electrolysis), fossil fuel hydrogen production with carbon sequestration, and biological techniques (algae and bacteria).

Vision of hydrogen 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.

A pathway for scaling up hydrogen use would build from the existing hydrogen industry. To foster the initial growth of distributed markets, small reformers and electrolyzers will provide hydrogen for small fleets of fuel cell-powered vehicles and distributed power supply. The next stage of development will include mid-sized community systems and large, centralized hydrogen production facilities with fully developed truck delivery systems for short distances and pipeline delivery for longer distances. As markets grow, costs will drop through economies of scale and technological advances; carbon emissions will decrease with commercialization of carbon capture, sequestration, and advanced direct conversion methods using photolytic, renewable, and nuclear technologies.

CHALLENGES

Multiple challenges must be overcome to achieve the vision of secure, abundant, inexpensive, and clean hydrogen production with low carbon emissions.

Hydrogen production costs are high relative to conventional fuels. With most hydrogen currently produced from hydrocarbons, the cost per unit of energy delivered through hydrogen is higher than the cost of the same unit of energy from the hydrocarbon itself. This is especially the case when the comparison is made at the point of sale to the customer, as delivery costs for hydrogen are also higher than for hydrocarbons. The large-scale, well-developed production and delivery infrastructures for natural gas, oil, coal, and electricity keep energy prices low and set a tough price point for hydrogen to meet.

Low demand inhibits development of production capacity. Although there is a healthy, growing market for hydrogen in refineries and chemical plants, there is little demand for hydrogen as an energy carrier. Demand growth will depend on the development and implementation of hydrogen storage and conversion devices, and on a demand pull from products such as hydrogen-powered cars and electric generators. Without demand for high-quality hydrogen in the merchant energy carrier market, there is little incentive for industry to completely develop, optimize, and implement existing and new technologies.

Current technologies produce large quantities of carbon dioxide and are not optimized for making hydrogen as an energy carrier. Existing production technologies can produce vast amounts of hydrogen from hydrocarbons but emit large amounts of carbon dioxide into the atmosphere. Existing commercial production methods (such as steam methane reformation, multi-fuel gasification, and electrolysis) require

technical improvements to reduce costs, improve efficiencies, and produce inexpensive, high-purity hydrogen with little or no carbon emissions.

Advanced hydrogen production methods need development. While wind, solar, and geothermal resources can produce hydrogen electrolytically, and biomass can produce hydrogen directly, other advanced methods for producing hydrogen from renewable and sustainable energy sources without generating carbon dioxide are still in early research and development phases. Processes such as nuclear thermo-chemical water splitting, photoelectrochemical electrolysis, and biological methods require long-term, focused efforts to move toward commercial readiness. Renewable technologies such as solar, wind, and geothermal need further development for hydrogen production to be more cost-competitive from these sources.

Public-private production demonstrations are essential. Stakeholders need a basic understanding of the different sources of hydrogen production before they will be willing to embrace the concepts. Demonstrations are the best way to gain the needed confidence. The large scale of some production processes, however, makes them particularly difficult and expensive to demonstrate.

PATHS FORWARD

The specific needs and actions required to address these barriers differ for each of the hydrogen production technologies. No single technology meets all of the criteria of the Vision; various combinations of the production technologies are likely to be used for different applications.

Enact policies that foster both technology and market development.

Government support for research and development should focus on developing advanced renewable and low-carbon-emitting methods plus carbon dioxide capture and sequestration technologies.

Improve gas separation and purification processes. The oxygen plant is one of the higher cost items in multi-fuel gasifiers; lowering this cost will improve the economics of hydrogen production. Small, low-cost, high-efficiency hydrogen purification methods are needed for distributed reformers that can generate hydrogen at residences or car-refueling stations. Although some purification technologies work well at large commercial sites, these are often difficult to scale down to the size needed for distributed generation.

Develop and demonstrate small reformers. Small reformers that run on natural gas, propane, methanol or diesel can provide hydrogen to some of the first fleets and retail sales points, reducing overall costs. The technology also needs further refinement for improved reliability, longer catalyst life, and integration with storage systems and fuel cells.

Optimize and reduce costs of electrolyzers. Efforts to improve the efficiency and lower the costs of electrolyzers must continue, as this production method is ideal for distributed generation and could offer early market opportunities. Although electrolysis is currently more expensive than thermal production, a better understanding of high-temperature and high-pressure electrolysis could bring costs down. In distributed hydrogen systems, the hydrogen produced on-site often requires compression (to pressures as high as 5,000 psi) for storage; high-pressure electrolysis could remove the need for this additional compression.

A near-term study should be conducted to develop measurable goals for electrolysis in terms of production efficiency, capital cost, and price. Specific goals will help to align and focus development efforts.

Develop advanced renewable energy methods that do not emit carbon dioxide. Photolytic processes use light energy to split water and produce hydrogen, potentially offering lower costs and higher efficiencies for collecting solar energy. Semiconductors that enable photoelectrochemical splitting of water need to become more efficient and less susceptible to corrosion in water. Biological systems may become a “low-tech” way to provide hydrogen, but they are still in the early stages of development.

Develop advanced nuclear energy methods to produce hydrogen. Research is needed to identify and develop methods for economically producing hydrogen with nuclear energy, which would avoid carbon emissions. Thermochemical water splitting using high-temperature heat from advanced nuclear reactors could be included in future nuclear plant designs.

Develop methods for large-scale carbon dioxide capture and sequestration. A cost-effective way to capture and sequester carbon dioxide would facilitate the production of vast quantities of hydrogen with low carbon emissions. Capture systems would need to be engineered into plant designs for steam methane reformers and multi-fuel gasifiers to lower the overall systems costs.

Demonstrate production technologies in tandem with applications. Demonstrations are expensive, especially since there may be little initial demand for the hydrogen produced. Demonstrations that integrate production technology with other elements of the hydrogen infrastructure, including a market use, will be more cost effective. These demonstrations should highlight safety and other benefits to stimulate market interest.

Demonstrations of hydrogen generation, purification, storage, dispensing, and fuel cell electricity generation should be pursued in the short term in major metropolitan areas. For technologies that need larger-scale testing and demonstration, an industrial-scale testing location should be developed to alleviate difficulties in finding acceptable sites.

CONCLUSION

Research, development, and demonstrations are needed to improve and expand methods of economically producing hydrogen. Production costs need to be lowered, efficiency improved, and carbon sequestration techniques developed. Better techniques are needed for both central-station and distributed hydrogen production. Efforts should focus on existing commercial processes such as steam methane reforming, multi-fuel gasifiers, and electrolyzers, and on the development of advanced techniques such as biomass pyrolysis and nuclear thermochemical water splitting, photoelectrochemical electrolysis, and biological methods.

The ability to capture and sequester carbon dioxide in a cost-effective way could open the door to making vast quantities of hydrogen with low carbon emissions.

How much hydrogen do we need?

Once applications for hydrogen as an energy carrier have become well established, the United States will require much more hydrogen than it now produces. An estimated 40 million tons of hydrogen will be required annually to fuel about 100 million fuel-cell powered cars, or to provide electricity to about 25 million homes.

Each of the following scenarios could produce 40 million tons per year of hydrogen:

Distributed Generation Production Methods

Electrolysis: 1,000,000 small neighborhood based systems could fuel some of the cars and provide some power needs.

Small reformers: 67,000 hydrogen vehicle refueling stations, which is about one third of the current gasoline stations.

Centralized Production Methods

Coal/biomass gasification plants: 140 plants each about like today's large coal fired plants.

Nuclear water splitting: 100 nuclear plants making only hydrogen

Oil and natural gas refinery: 20 plants, each the size of a small oil refinery, using oil and natural gas in multi-fuel gasifiers and reformers.

"A Production Mosaic"

Many factors will affect the choice of production methods, how they will be used, and when they might be demonstrated and commercialized. Visualizing a mosaic of future production methods provides a perspective for the Roadmap. The combination of distributed and centralized production, plus advanced methods that are not yet available, could be combined to create a future industry producing 40 million tons of hydrogen per year. Here is one scenario:

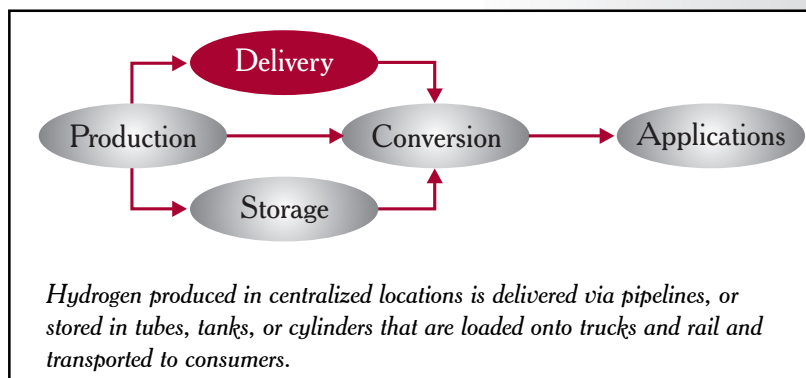
100,000 neighborhood electrolyzers	4 million tons
15,000 small reformers in refueling stations	8 million tons
30 coal/biomass gasification plants	8 million tons
10 nuclear water splitting plants	4 million tons
7 large oil and gas SMR/gasification refineries	16 million tons

4 Delivery

INTRODUCTION

A key element of the overall hydrogen energy infrastructure is the delivery system that moves the hydrogen from its point of production to an end-use device. Delivery system requirements necessarily vary with the production method and end-use application.

Hydrogen delivery today: At present, hydrogen is produced in a limited number of plants and is used for making chemicals or upgrading fuels. It is currently transported by pipeline or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail car or barge.



As in the case of natural gas distribution, pipelines are employed as an efficient means to supply customer needs. The pipelines are currently limited to a few areas of the United States where large hydrogen refineries and chemical plants are concentrated, such as in Indiana, California, Texas, and Louisiana. The pipelines are owned and operated by merchant hydrogen producers.

Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100 to 200 miles from the production or distribution facility. For long-distance distribution of up to 1,000 miles, hydrogen is usually transported as a liquid in super-insulated, cryogenic, over-the-road tankers, railcars, and barges and is then vaporized for use at the customer site.

Vision of hydrogen 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.

CHALLENGES

A comprehensive delivery infrastructure for hydrogen faces numerous scientific, engineering, environmental, institutional, and market challenges.

An economic strategy is required for the transition to a hydrogen delivery system. Since fueling economics depend on volume, the chicken and egg dilemma (which comes first: fuel or end use applications?) impedes the installation of an effective infrastructure. There is no simple reconciliation between the level of investments required to achieve low costs and the gradual development of the market. Current investments in delivery systems need to be justifiable beyond 2020 to support adequate returns on investment.

Full life-cycle costing has not been applied to delivery alternatives. Any strategy to select appropriate delivery systems should involve full life-cycle costing of the options. Life-cycle cost analyses should compare gaseous and liquid hydrogen delivery, and hydrogen carrier media such as metal and chemical hydrides, methanol, and ammonia. Multiple delivery infrastructures may be necessary, which could add to the cost of transitioning to a hydrogen economy.

Hydrogen delivery technologies cost more than conventional fuel delivery. The high cost of hydrogen delivery methods could lead to the use of conventional fuels and associated delivery infrastructure up to the point of use, and small-scale conversion systems to make hydrogen onsite. However, cost effective means do not currently exist to generate hydrogen in small-scale systems.

Current dispensing systems are inconvenient and expensive. Customers expect the same degree of convenience, cost performance, and safety when dispensing hydrogen fuel as when dispensing conventional fuels. Current hydrogen fueling solutions and designs are not sufficiently mature.

PATHS FORWARD

Current delivery systems will need to expand significantly to deliver hydrogen to all regions of the country in a safe and affordable manner. Distributed hydrogen production is likely to play a significant role, but alternative delivery systems tailored to consumer applications (such as the transport of hydrogen in safe, solid metal alloy hydrides, carbon nanomaterials, and other chemical forms) need to be developed to transport hydrogen to end-use sites on an as-needed basis.

Hydrogen Delivery Challenges

Scientific and Engineering	Environmental and Institutional	Market
<p>Cost-effective means of converting H₂ carriers to H₂ do not exist</p> <p>Technical solutions to H₂ dispensing for self-service refueling facilities need further experience and development</p> <p>Proprietary data on materials needed for design are not published</p> <p>Lack of a firm understanding of required H₂ purity for fuel cells</p> <p>Lack of design criteria for multi-gas pipelines</p>	<p>Codes and standards do not include H₂. Lack of harmonization national and international codes</p> <p>Lack of full social costing of alternatives. Defined value for carbon</p> <p>Lack of life-cycle environmental impact to all options</p> <p>Liquefaction is energy and greenhouse gases intensive</p> <p>Conflicting local vs. state or national interests is a barrier to community acceptance of H₂</p> <p>Environmental concerns with fossil carbon-based feedstock</p> <p>Lack of experience and knowledge for operation and maintenance of H₂ technologies</p> <p>Mandates are difficult to establish</p>	<p>Lack of an economic strategy from today's fuels to a hydrogen future</p> <p>Cost of H₂ technologies higher than current technologies</p> <p>Current dispensing system designs do not meet customer expectations for cost, and convenience</p> <p>Access to affordable capital</p> <p>Current weight and capacity of tube trailers</p> <p>Compressed hydrogen has low energy density</p> <p>Poor economics for transport of gases over long distance</p>

Develop a demonstration rollout plan. A hydrogen delivery infrastructure needs to be started in several regions of the United States. Government-sponsored pilot testing of refueling systems, similar to those for compressed natural gas, would help establish a basis for certifying components of fuel stations. Demonstration programs would stimulate development of delivery and end-use technologies. Regional delivery networks in a number of states would be a good approach to build out the systems.

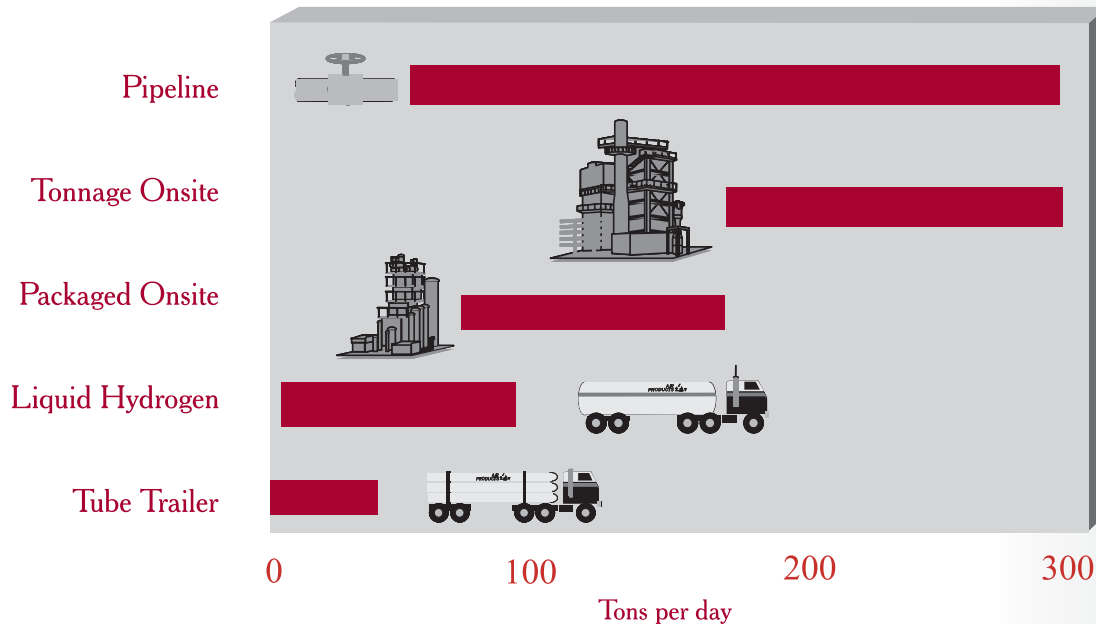
Develop a consensus view on total costs of delivery alternatives. Analyses of the total costs of delivery alternatives need to be conducted. Analyses should weigh options that address all potential fuel delivery points, the cost of maintaining existing fuel infrastructure, and the suitability of the existing infrastructure for future hydrogen use.

Increase research and development on delivery systems. Improvements are needed in areas such as hydrogen detectors; odorization; materials selection for pipelines, seals, and valves; and transportation containers for hydrogen. Technology validation should address research and development needs for fueling components such as high-pressure, breakaway hoses; hydrogen sensors; compressors; on-site hydrogen generation systems; and robotic fuelers.

Researchers need to test the feasibility of delivery methods from centralized and distributed hydrogen production plants as well as compressors, storage systems, and other components integrated into complete delivery systems.

Testing and validation should be ongoing. An organization should be established to perform testing and certification and to identify components that require validation and testing protocols. The organization should include representatives of insurance companies, government agencies, National Laboratories, and industry.

Hydrogen Delivery Methods



Source: Air Products and Chemicals, Inc.

CONCLUSION

The realization of a hydrogen delivery infrastructure is hampered by the lack of a transition strategy, appropriate codes and standards, the comparatively high cost of hydrogen delivery, and inconvenient dispensing systems.

Installation of hydrogen delivery systems is certainly feasible for industrial markets, which are relatively limited in size and scope. Fuel applications of hydrogen will need to meet much lower economic cost targets than those for current industrial markets. Since scale is critical to cost reductions, care should be taken to build the necessary scale into all government policy and demonstration programs.

Efforts should focus on the development of better components for existing delivery systems, including hydrogen sensors, pipeline materials, compressors, and high-pressure breakaway hoses. To address the “chicken and egg” fuel/use dilemma, demonstration projects should emphasize testing the hydrogen infrastructure components in applications such as fueling stations and power parks.

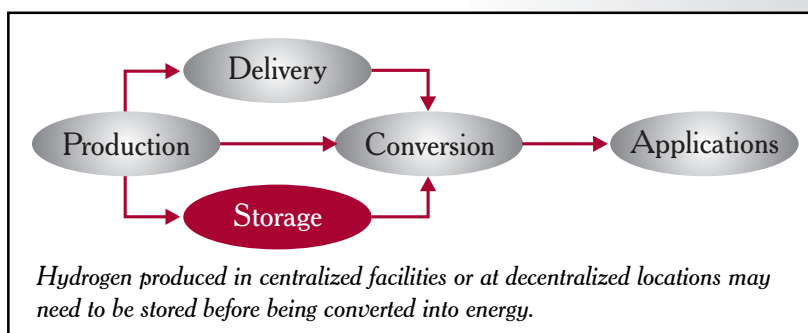
Hydrogen Delivery - Paths Forward

Needs	Partners
Building codes and equipment standards	Industry with support and funding from government agencies
Multi-state delivery demonstrations and showcases	Industry-led cost-shared partnership with Federal and state governments
Consensus on total costs of fuel alternatives	Government-led and funded with support from National Labs and universities
Improved financial incentives for delivering hydrogen to markets	Federal and state government leadership
Hydrogen economy transition strategy quantified with milestones and targets	Industry- and government-led with support from National Labs and universities

5 Storage

INTRODUCTION

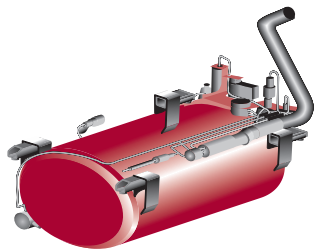
Storage issues cut across the production, transport, delivery, and end-use applications of hydrogen as an energy carrier. Mobile applications are driving the development of safe, space-efficient, and cost-effective hydrogen storage systems, yet other applications will benefit substantially from all technological advances made for these on-vehicle storage systems.



Hydrogen storage today: Hydrogen can be stored as a discrete gas or liquid or in a chemical compound. Currently available technologies permit the physical storage, transport, and delivery of gaseous or liquid hydrogen in tanks and pipeline systems. The storage of compressed hydrogen gas in tanks is the most mature technology, though the very low density of hydrogen translates to inefficient use of space aboard a vehicle. This inefficiency can be mitigated with higher compression, such as 5,000 to 10,000 psi. Storage tank designs are advancing with increased strength-to-weight ratio materials and optimized structures that provide better containment, reduced weight and volume, improved impact resistance, and improved safety.



Liquid hydrogen takes up less storage volume than gas but requires cryogenic containers. Furthermore, the liquefaction of hydrogen is an energy-intensive process and results in large evaporative losses—about one-third of the energy content of the hydrogen is lost in the process.

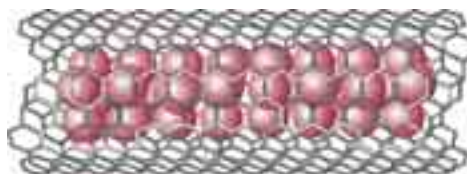


Hydrogen can be stored at high densities as reversible metal hydrides or adsorbed on carbon structures. When the hydrogen is needed, it can be released from these materials under certain temperature and pressure conditions. Complex-based reversible hydrides such as alanates have recently demonstrated improved weight performance over metal hydrides along with modest temperatures for hydrogen recovery. The most promising carbon materials for hydrogen storage at this time appear to be carbon nanotubes.

Hydrogen can be stored at high densities as reversible metal hydrides or adsorbed on carbon structures. When the hydrogen is needed, it can be released from these materials under certain temperature and pressure conditions. Complex-based reversible hydrides such as



Chemical hydrides are emerging as another alternative to direct hydrogen storage. The chemical hydrides considered for storage applications are a class of compounds that can be stored in solution as an alkaline liquid. Since the hydrogen is chemically



bound in the compound and released by a catalyzed process, chemical hydrides present an inherently safer option than the storage of volatile and flammable fuel, be it hydrogen, gasoline, methanol, etc. The challenges associated with chemical hydrides include lowering the cost of the “round-trip” chemical hydride process (which requires recycling of spent “fuel”), increasing overall “well to wheels” energy efficiency, and development of infrastructure to support the production, delivery, and recycling of the chemical hydrides for transportation and other uses.

No current technology appears to satisfy all of the desired storage criteria sought by manufacturers and end users. Compressed hydrogen storage is a mature technology, though improvements in cost, weight, and volume storage efficiency must continue to be made. Several automotive manufacturers are considering liquid hydrogen storage because of its good volumetric storage efficiency; however the special handling requirements, long-term storage losses, and cryogenic liquefaction energy demands currently detract from its commercial viability. Metal hydrides offer the advantages of lower pressure storage, conformable shapes, and reasonable volumetric storage efficiency, but have weight penalties and thermal management issues. Although chemical hydrides present a potentially safer and more volumetrically efficient option, there are a number of challenges that must be addressed, including cost, recycling, overall energy efficiency, and infrastructure. Adsorbing materials with high surface areas are emerging, but the design of practical systems awaits a better understanding of the fundamental adsorption/desorption processes and development of high-volume manufacturing processes for the materials.

Vision of hydrogen 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.

Hydrogen Storage Alternatives

Compressed Fuel Storage	<ul style="list-style-type: none"> ■ Cylindrical tanks ■ Quasi-conformable tanks
Liquid Hydrogen Storage	<ul style="list-style-type: none"> ■ Cylindrical tanks ■ Elliptical tanks ■ Cryotanks ■ HP liquid tanks
Solid State Conformable Storage	<ul style="list-style-type: none"> ■ Hydride materials ■ Carbon adsorption
Chemical Hydrides	<ul style="list-style-type: none"> ■ Off-board recycling

CHALLENGES

Hydrogen storage must meet a number of challenges before hydrogen can become an acceptable energy option for the consumer. The technology must be made transparent to the end user—similar to today’s experience with internal combustion gasoline-powered vehicles. Specific challenges include the following:

Current research and development efforts are insufficient. Hydrogen storage is a critical enabling element in the hydrogen cycle, from production and delivery to energy conversion and applications. Improved storage technologies are needed to satisfy end-user expectations and foster consumer confidence in hydrogen-powered alternatives. A substantial research and development investment in hydrogen storage technologies will be required to achieve the performance and cost targets for an acceptable storage solution.

New media development is needed to provide reversible, low-temperature, high-density storage of hydrogen. These storage characteristics generally describe the technical goals for some of the solid-state materials, including hydrides and carbon adsorption materials. The ultimate hydrogen storage system for meeting manufacturer, consumer, and end-user expectations would be low in cost and energy efficient, provide fast-fill capability, and offer inherent safety.

Energy storage densities are insufficient to gain market acceptance. This barrier directly relates to making hydrogen storage transparent to the consumer and end user. Specifically, transparency would mean a hydrogen storage system that enables a vehicle to travel 300 to 400 miles and fits in an envelope that does not compromise either passenger or storage space. Fundamental limitations on hydrogen density will ultimately limit storage performance. The performance of vehicles, therefore, depends on the overall system performance—the combined vehicle efficiency, energy conversion efficiency, and storage efficiency.

Low demand means high costs. As there are few hydrogen-fueled vehicles on the road today, the more mature compressed and liquid hydrogen storage technologies are quite expensive. High-pressure cylinders will be amenable to high-volume production, once demand warrants it. Raw material costs could also be reduced substantially if there were sufficient demand. For emerging technologies, manufacturing feasibility and cost reduction measures will play integral roles in the technology development process. The initially low rates at which automakers expect to introduce fuel cell vehicles will present a challenge to the commercialization and cost reduction of hydrogen storage technologies.

PATHS FORWARD

Achieving the Vision for hydrogen storage will require coordinated activities that address the challenges.

Develop a coordinated national program to advance hydrogen storage materials. A fully funded national program is needed to improve the performance and

What Consumers Want

With transparency an acknowledged target, it is important to understand consumers’ expectations for fuel storage on a vehicle. Simply put, consumers do not think about fuel storage. They do not see the fuel tank. They expect maximum passenger and trunk space. They expect 300 to 400 miles range on “a tank of gas” before having to fill-up. They expect to fill up their “tank” in less than 3-5 minutes. They are used to self-serve “gas stations” that are virtually foolproof, with a simple trigger-type nozzle that starts with a push of a button or flick of a lever. They expect to be able to refuel at the corner gas station, although refueling at home would be a nicety. Probably the only time most consumers in the United States think about fuel, let alone fuel storage, is when fuel prices rise to \$2.00 per gallon of gasoline.

Hydrogen Storage Tank Classifications

- Type 1: all metal cylinder
- Type 2: load-bearing metal liner hoop wrapped with resin-impregnated continuous filament
- Type 3: non-load-bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament
- Type 4: non-load-bearing non-metal liner axial and hoop wrapped with resin-impregnated continuous filament
- Type 5 (Other): type of construction not covered by Types 1 to 4 above.

Source: European Integrated Hydrogen Program

reduce the cost of hydrogen storage. Emerging hydrogen applications require a range of near-term advances in high-pressure storage technology: improved weight efficiency, service pressure capability, conformable or quasi-conformable shapes, system integration and packaging, “smart” tanks with integrated or embedded sensors, and system costs. Advanced storage materials that show promise for hydrogen storage include alanates, carbon structures, chemical hydrides, and metal hydrides. While promising, these storage technologies are still in the developmental stage. Further research and development efforts are required to understand how to produce and contain the materials, fill and discharge hydrogen from them, manage the pressure and thermal properties, integrate the materials into a practical system, and meet infrastructure requirements.

Elevate research and development in hydrogen storage to a level commensurate with its importance. Storage technologies are integral to the production, transport, delivery, and application of hydrogen as an energy carrier. Since mobile applications impose severe size and weight constraints, they are a major driver behind efforts to develop safe, space-efficient, and cost-effective hydrogen storage systems—but other applications will also benefit from any technological advances made for on-board systems.

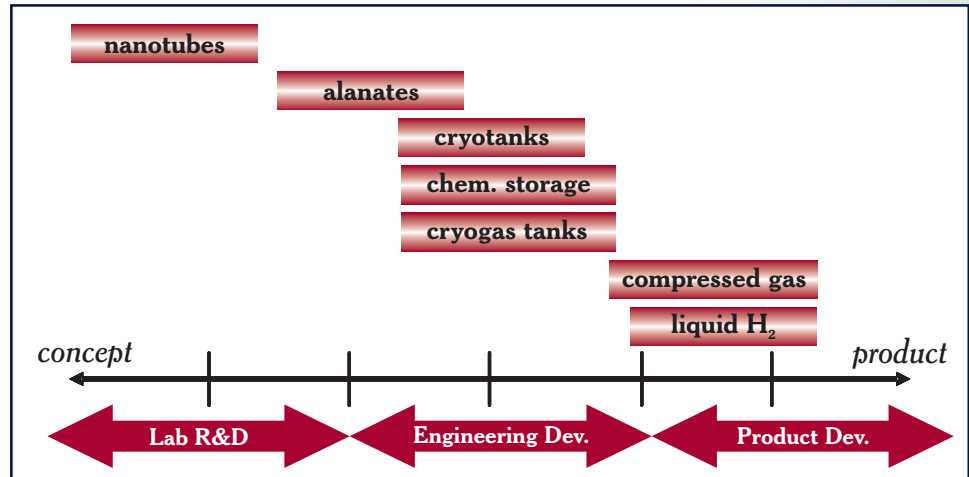
Current research and development specifically allocated to advanced hydrogen storage technologies is inadequate to fully investigate, develop, and demonstrate all materials. Research sponsored by the U.S. Department of Energy, the U.S. Department of Transportation, and the U.S. Department of Defense should be coordinated, with similar activities sponsored by industry.

Initiate a program to support development of high-risk technologies. None of the currently known technologies satisfy all the desired hydrogen storage attributes sought by manufacturers and end users. Each has its advantages and disadvantages. While improvements in currently known storage technologies are likely, a technology breakthrough may be necessary to achieve an “ultimate” storage device. This is an excellent example of an area of research where there needs to be freedom, and associated funding, to pursue non-obvious technology solutions not currently known and independent of traditional performance metrics. This approach is high-risk, but carries the potential for high payback.

Develop a mass production process for hydrogen storage media. Currently, no market force is driving efforts to reduce raw material costs and develop efficient mass production processes. Even the more mature compressed and liquid hydrogen storage

technologies are expensive due to an absence of high-volume demand. Emerging technologies still in the laboratory, including hydrides, alانات, and carbon adsorption materials, have further to go along the path to commercialization and mass production. Fundamental improvements in hydrogen storage processes remain to be fully understood and optimized. Once the materials have been optimized in the laboratory, practical integrated storage systems must be developed and demonstrated. At that point, design and scale-up for production and cost must be addressed.

Storage Technology Status

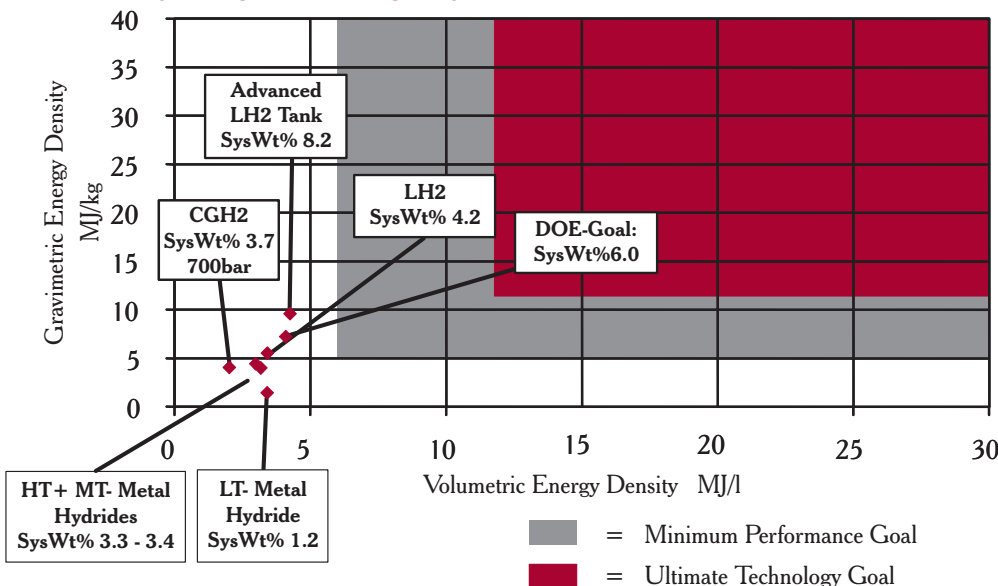


Source: George Thomas, Ph.D.

CONCLUSION

The lack of low-cost and lightweight storage devices as well as commercially available and cost-competitive fuel cells interferes with the implementation of hydrogen as an energy carrier. For a “hydrogen economy” to evolve, consumers will need to have convenient access to hydrogen, and storage devices will be one of the keys. Better hydrogen storage systems will offer easy access to hydrogen for vehicles, distributed energy facilities, or central station power plants.

Gravimetric Energy Density vs. Volumetric Energy Density of Fuel Cell Hydrogen Storage Systems



These hydrogen storage targets are based upon conventional vehicle architectures and vehicle performance requirements.

Source: General Motors

The most challenging application is the light-duty vehicle or, more specifically, the automobile. Automobiles impose the greatest constraints with respect to available space on-board the vehicle and the greatest consumer expectations for energy density (vehicle range). In the near-term, fuel cell vehicles are likely to be introduced first in fleet applications. Since fleet applications are apt to have centralized refueling facilities, a vehicle range of 100 to 150 miles (160 to 241 kilometers) would be acceptable. In terms of mass of hydrogen, this range could be achieved with about 3 kilograms of hydrogen supplying a fuel cell vehicle. Mature compressed and liquid hydrogen storage technologies of reasonable size and weight could achieve this short-term goal.

In the longer term, average consumers will expect fuel cell vehicles to provide the same cost, convenience, and operational characteristics as gasoline-powered vehicles. In fact, it is likely that fuel cell vehicles will have to offer a significant value proposition to encourage consumers to adopt a new technology rather than continue with something that is tried and true. Vehicle range will be an important factor to consumers, especially as a hydrogen refueling infrastructure begins to develop. Fuel cell vehicle ranges of 300 to 400 miles (480 to 644 kilometers) will be needed, requiring roughly 5 kilograms of hydrogen to be stored on-board. Advanced storage methods, including advancements in compressed storage, alanate hydrides, cryogas tanks, and carbon nanostructures, will have to emerge from the laboratory to reduce hydrogen storage system size, weight, and cost without sacrificing safety or consumer convenience.

6 Conversion

INTRODUCTION

Hydrogen can be used both in engines and in fuel cells. Engines can combust hydrogen in the same manner as gasoline or natural gas, while fuel cells use the chemical energy of hydrogen to produce electricity and thermal energy. Since electrochemical reactions are more efficient than combustion at generating energy, fuel cells are more efficient than internal combustion engines.

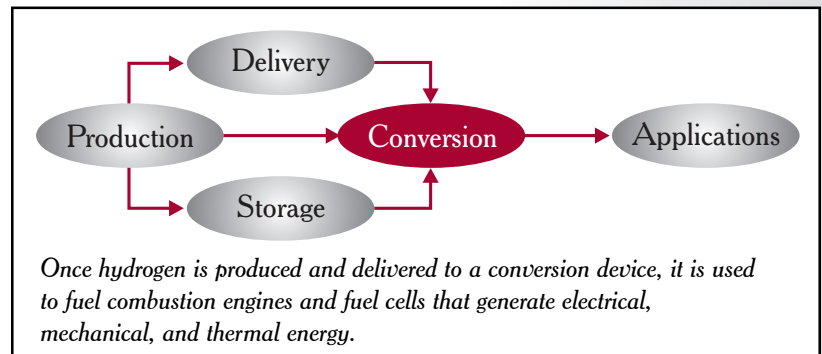
Hydrogen conversion today: The use of hydrogen in engines is a fairly well developed technology—the National Aeronautics and Space Administration and the Department of Defense use it in the space shuttle’s main engines and unmanned rocket engines. Other combustion applications are under development, including new combustion equipment designed specifically for hydrogen in turbines and engines. Vehicles with hydrogen internal combustion engines are now in the demonstration phase, and the combustion of hydrogen blends is being tested.

Fuel cells are in various stages of development. Current fuel cell efficiencies range from 40 to 50 percent at full power and 60 percent at quarter-power, with up to 80-percent efficiency reported for combined heat and power applications.

Phosphoric-acid fuel cells are the most developed fuel cells for commercial use. Many stationary units have been installed to provide grid support and reliable back-up power, and mobile units are powering buses and other large vehicles.

Polymer-electrolyte membrane fuel cells are being developed and tested for use in transportation, stationary, and portable applications. Interest in polymer-electrolyte membrane fuel cells has experienced a tremendous upsurge 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 and space missions (to provide electricity and drinking water for astronauts). Currently they are being tested for transportation applications.



Hydrogen Conversion Technologies and Applications

Technology	Application
Combustion	
Gas Turbines	<ul style="list-style-type: none"> ■ Distributed power ■ Combined heat and power ■ Central station power
Reciprocating Engines	<ul style="list-style-type: none"> ■ Vehicles ■ Distributed power ■ Combined heat and power
Fuel Cells	
Polymer Electrolyte Membrane (PEM)	<ul style="list-style-type: none"> ■ Vehicles ■ Distributed power ■ Combined heat and power ■ Portable power
Alkaline (AFC)	<ul style="list-style-type: none"> ■ Vehicles ■ Distributed power
Phosphoric Acid (PAFC)	<ul style="list-style-type: none"> ■ Distributed power ■ Combined heat and power
Molten Carbonate (MCFC)	<ul style="list-style-type: none"> ■ Distributed power ■ Combined heat and power
Solid Oxide (SOFC)	<ul style="list-style-type: none"> ■ Truck APVs ■ Distributed power ■ Combined heat and power

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 are also a good fit for portable power and transportation applications, especially large trucks.

Fuel cells can and currently do run on fossil fuel reformat.

Vision of hydrogen energy 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.

The commercial production, delivery, and storage of hydrogen will go hand in hand with the commercial conversion of hydrogen into valuable energy services and products, such as electricity and thermal or mechanical energy. As shown in the table above, the technologies appropriate for commercial conversion include established technologies, such as combustion turbines and reciprocating engines, as well as less developed technologies with great potential, such as fuel cells. Current products embodying these technologies have the potential to provide safe, clean, and affordable energy services in all sectors of our global economy.

CHALLENGES

All of today’s conversion products, demonstration models, and prototypes possess some deficiencies; they cannot yet provide, at an affordable cost, the level and quality of energy services demanded by a broad base of consumers. While fuel cell technologies have generated much excitement, they are still in various stages of maturity. Most have not been manufactured in large quantities, and numerous performance issues—including durability, reliability, and cost—remain to be resolved. Combustion turbines and engines that use hydrogen or hydrogen/natural gas blends, already in use in both mobile and stationary applications, are much closer to satisfying these criteria than are fuel cells.

No single fuel cell technology has met all the basic criteria for performance, durability, and cost. Basic and applied research in materials science and electrochemistry is required to improve the design and operation of all fuel cell

Top Priority Hydrogen Conversion Challenges

Scientific	Engineering	Market	Institutional
<p>Knowledge gaps in materials science/technology and electrochemistry</p> <p>Knowledge gaps in hydrogen combustion properties</p>	<p>Questions on fuel cell performance and durability</p> <p>High fuel cell manufacturing costs</p> <p>Unproven hydrogen-burning engine and turbine performance</p> <p>Questions about flame management and impacts on engine and turbine designs</p>	<p>No “value proposition” for using hydrogen rather than fossil fuels (externality costs for fossil fuels not in fuel prices)</p> <p>Lack of profitable business models for widespread installation of distributed energy systems and CHP</p> <p>Large financial risk of being overtaken by competing technologies</p>	<p>Lack of product safety codes for hydrogen using devices</p> <p>Lack of safety standards for installation and operation of hydrogen conversion systems in vehicle and buildings</p> <p>Lack of national and state public policies for expanding the use of hydrogen conversion devices</p>

technologies and provide an ongoing basis for substantial cost reduction and performance improvements. In polymer-electrolyte membrane fuel cells, for example, researchers still need a better understanding of the purity levels of graphite; durability of membranes; gas diffusion layers; bipolar plates; and long-term contamination issues. In solid-oxide fuel cells, researchers are working to expand their understanding of interconnected materials and the processes that underlie sealing and joining.

Fuel cells require enhanced materials, membranes, and catalysts to meet both engineering and cost criteria. For all types of fuel cells except phosphoric acid, reliability of performance and durability over extended hours of operation remain to be proven. Phosphoric-acid fuel cells are the only type of fuel cells with substantial commercial experience, but efforts to bring down their manufacturing cost have not yet paid off. Questions also remain about the performance of all types of fuel cells under diverse climatic conditions and geographic locations. Manufacturing scale-up issues and the associated need to establish high-volume demand are major barriers in achieving cost reductions.

Research is needed to fill in critical knowledge gaps. Researchers require better information about the flame characteristics of hydrogen combustion and the impacts of conversion technologies on reciprocating engine and turbine designs. Better knowledge is also needed to guide the use of advanced materials in hydrogen combustion systems. Existing databases need to be populated with more performance data for hydrogen-burning engines and turbines operating over extended periods; performance data needs include efficiency, emissions, and safety, for both mobile and stationary applications.

Market and institutional barriers hinder development of cost-competitive hydrogen conversion devices. Customers do not see a robust value proposition that convinces them to choose hydrogen conversion products. Substantial cost reduction will be essential—particularly without a bridging incentive or government mandate fostering use of hydrogen conversion products rather than lower-cost conventional fuels and products. In the absence of such policies, conventional fuels and conversion devices will continue to be the only practical option for consumers. Fuel cell manufacturers also face problems in developing innovative safety technologies and achieving profitable operations prior to the development of large-scale markets.

PATHS FORWARD

Over the last decade, most of the enhancements to fuel cell performance have been achieved through incremental improvements to known materials and processes. Investing in efforts to increase fundamental understanding of current materials, interfaces, and processes will support important advances, such as the following:

- Better electrocatalysts to reduce the cathode over-potential and/or tolerate carbon monoxide at the anode
- Non-precious metal catalysts to dramatically reduce cost
- Higher-temperature proton-exchange membrane fuel cells to facilitate thermal management and improve combined heat and power potential
- Lower-temperature oxide-ion conductors to enable moderate-temperature solid-oxide fuel cells and broaden materials choices, thus lowering system costs

Continue research and development on fuel cells and combustion engines.

Fundamental research is needed to advance scientific understanding of the materials used in fuel cells, particularly their chemical and physical properties and their interactions.

This research will require a three-pronged effort in materials science, interfaces, and electrochemistry. Advancements in these areas could lead to new designs and open the possibility of using lower-cost and easier-to-manufacture materials. Significant advances are needed for stack materials, oxygen cathodes, and membranes.

Researchers need better methods for characterizing materials as well as better understanding of advanced ceramic materials and membrane degradation mechanisms. Improvements in these areas could lead to the development of polymer-electrolyte membrane fuel cells that operate at higher temperatures, and solid-oxide fuel cells that operate at lower temperatures.

Other key research needs include engine and turbine materials that resist corrosion and operate efficiently at higher temperatures, more durable and lower-cost sensors and instrumentation, and better-performing hydrogen-natural gas fuel blends.

Continuing investment in technology development and manufacturing methodologies, starting with components and stacks and continuing through system integration, will hasten commercialization. Industry-driven, cost-shared partnerships with government, supported by universities and laboratories, could lead to catalysts with better performance and lower costs.

Enhance manufacturing capabilities for fuel cells. Techniques are needed for handling high fuel cell production volumes and achieving better consistency and quality control. Advancements in this area are one of the surest means to achieving the large cost reductions needed to move fuel cells from niche to mass markets. Improvements are also needed in the cost and integration of balance-of-plant components, such as power conditioning, thermal storage and management, water management, and fuel processing equipment.

Top Priority Hydrogen Conversion Needs

Fuel Cells	Combustion	Demonstrations	Codes and Standards	Analysis
Expanded fundamental research program in advanced materials, interfaces and electrochemistry	Higher efficiency and lower cost engine and turbine designs	Expand number of sites to include wider range of technologies, applications, and environmental conditions	Product safety standards	More credible market analysis
Lower cost designs	Instrumentation and controls optimized for hydrogen combustion parameters	Expand information dissemination	Building codes (fire, safety, plumbing)	Catalog existing research results and disseminate widely
Enhanced manufacturing capabilities	Analysis of hydrogen-natural gas blending for lower emissions	Expand validation of hydrogen combustion	Vehicle standards	Software tools to simulate collisions to enhance fuel cell engine designs
Lower cost balance-of-plant components			Utility interconnection standards	

Develop new engine and turbine designs to lower nitrogen oxide emissions when combusting hydrogen-natural gas blends. A full range of possibilities for blending hydrogen with natural gas merit further exploration as a low-emissions strategy. New engine and turbine controls should be developed to optimize performance when used in conjunction with hydrogen storage devices. Use of catalytic combustion techniques is another promising area in need of further exploration.

Collect more and better information on operating performance at existing demonstration sites. Improved instrumentation and expanded data collection efforts are required to facilitate analysis of the full range of cost, efficiency, and emissions parameters for all mobile and stationary applications under a wider range of environmental conditions. More extensive tests of the reliability and durability of advanced materials are also needed, particularly for polymer-electrolyte membrane and solid-oxide fuel cells. At the same time, better market analysis is needed to provide the financial community with an improved understanding of the potential for fuel cells and hydrogen-using engines and gas turbines.

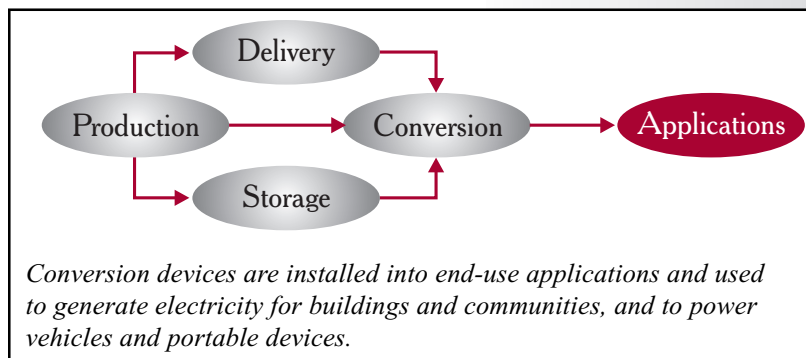
CONCLUSION

Engines, combustion turbines, and fuel cells can convert hydrogen into useful forms of energy. Research and development are needed to lower costs and enhance manufacturing capabilities for fuel cells and to develop higher-efficiency and lower-cost designs for engines and turbines. Industry should focus its efforts 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 blends for combustion. Government should assist in developing better information on the fundamental properties of hydrogen combustion and improving fundamental understanding of advanced materials, electrochemistry, and interfaces for fuel cells.

7 Applications

INTRODUCTION

Hydrogen can be used in conventional power generation technologies, such as automobile engines and power plant turbines, or in fuel cells, which are relatively cleaner and more efficient than conventional technologies. Fuel cells have broad application potential in both transportation and electrical power generation, including on-site generation for individual homes and office buildings.



Transportation applications today:

Transportation applications for hydrogen include buses, trucks, passenger vehicles, and trains. Technologies are being developed to use hydrogen in both fuel cells and internal combustion engines, including methanol systems.

Nearly every major automaker has a hydrogen-fueled vehicle program, with various targets for demonstration between 2003 and 2006. The early fuel cell demonstration programs will consist of pilot-plant “batch-builds” of approximately 10 to 150 vehicles. These early vehicles are most likely to be deployed in fleets with a centralized or shared re-fueling infrastructure to limit capital investment. Information obtained from these vehicle demonstrations will then be used to help determine how and when to advance to the next level of production.

Hydrogen-fueled internal-combustion engine vehicles are viewed by some as a near-term, lower-cost option that could assist in the development of hydrogen infrastructure and hydrogen storage technology. A key advantage of this option is that hydrogen-fueled internal-combustion engines vehicles can be made in larger numbers when demand warrants.

Stationary power generation today: Stationary power applications include back-up power units, grid management, power for remote locations, 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). Although commercial fuel cells are on the market, the industry is still in its infancy. Most existing fuel cell systems are being used in commercial settings and operate on reformat from natural gas. Widespread availability of hydrogen would allow the introduction of direct hydrogen units—simpler systems with lower cost and increased reliability.

In general, combustion-based processes, such as gas turbines and reciprocating engines, can be designed to use hydrogen either alone or mixed with natural gas. These technologies tend to have applications in the higher power ranges of stationary generation.

Portable power generation today: Portable applications for fuel cells include consumer electronics, business machinery, and recreational devices. Many participants in the fuel cell industry are developing small-capacity units for a variety of portable and

Characteristic Requirements of Transportation vs. Stationary Applications

Characteristic	Transportation	Stationary
Max Power	50 - 100 kW	2 - 200 kW (Multi unit housing)
Design Life	5,000 hours	50,000 hours
Cost	\$50 - 100/ kW	\$300 - 1000/ kW
Electrical Output	High Voltage AC or DC	48 V DC to 220 V AC
Efficiency	Very High	Very High
Power Range	20 to 1	10 to 1
Power Density (Volume)	Very High	Moderate
Specific Power (Weight)	Very High	Moderate
Operation	Intermittent	Continuous (24/7)
Energy Storage	Possibly	Possibly
Transient Response	1/10 of seconds	1/1000 of seconds
Short Term Fuel	Gasoline and diesel	Natural Gas/Propane
Long Term Fuel	Hydrogen	Hydrogen

premium power applications ranging from 25-watt systems for portable electronics to 10-kilowatt systems for critical commercial and medical functions. Most of these portable applications will use methanol or hydrogen as the fuel. In addition to consumer applications, portable fuel cells may be well suited for use as auxiliary power units in military applications.

Vision of hydrogen 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.

CHALLENGES

To achieve this vision for hydrogen applications, the following challenges will need to be overcome.

Transportation, stationary, and portable applications require technological and engineering solutions. Transportation applications lack affordable and practical hydrogen storage with sufficient volumetric and gravimetric densities. The absence of a storage solution severely hinders investment in infrastructure development as different storage mediums could result in substantially different infrastructure strategies. There is also a lack of reliable, inexpensive, and efficient reformation technologies.

Customers must accept hydrogen technologies and fuel cell vehicles. Fuel cell vehicles are in the early stages of development and the first vehicles are likely to fall short of consumer expectations (e.g., range, cold-weather capability). By comparison, conventional internal-combustion engine vehicles have had the benefit of more than 100

years of technological refinement as well as relatively reliable, low-cost gasoline to power them. Automakers continue to produce conventional cars that are progressively cleaner and more fuel-efficient.

The hydrogen fuel infrastructure for fuel cell vehicles (without on-board reformation) will be deployed gradually, and is likely to be severely limited in the early years. In the early stages of commercialization, automakers are also likely to put a limited offering of model types on the market, restricting consumer choices. Most of the benefits that hydrogen-fueled vehicles offer over conventionally fueled vehicles are societal in nature (e.g., reduced carbon dioxide and criteria emissions, energy security) and will not be fully realized until many years after market introduction. In addition, hybrid electric and gasoline vehicles will be coming on to the market in the near-term, and could compete with hydrogen-fueled vehicles.

Although conventional technologies (with modifications) can offer early market entry for hydrogen as an energy carrier, conventional technologies will continue to hold a major market advantage in terms of vehicle range. With their decreased energy density, today's hydrogen-fueled vehicles have ranges of 200 to 250 miles—far short of the 380 to 400 miles offered by contemporary hydrocarbon vehicles. Optimized hydrogen-fueled conventional technologies have been demonstrated that might achieve efficiencies close to the anticipated levels of fuel cells, with emissions that are near zero. Vehicles need to be redesigned for parity in range, or the public needs to be convinced of the benefits of a hydrogen-fueled vehicle to increase its perceived value.

PATHS FORWARD

Conduct research and development to address critical challenges to a hydrogen vision. Transportation and stationary applications will require development of low-cost and durable fuel cell stacks and systems. Development needs include high-temperature membranes for fuel cells; low-cost, fast-response, and low-power-consumption sensors and controls; low-cost, reliable, subsystem components such as compressors, pumps, and power electronics; and low-cost, reliable, hybrid batteries and ultra-capacitors.

In transportation applications, reformer research should be directed to enable near-term end use of hydrogen prior to the development of a nationwide hydrogen delivery system. Hydrogen storage research for vehicles should focus on systems that have the capability to match the driving range of equivalent gasoline vehicles. Development should focus on systems that are safe, have low weight and small size, and are cost competitive. Storage systems will have to be compatible with the fueling infrastructure, and the safety of storage system designs should be ensured through the development of codes and standards.

Combustion strategies and after-treatments must be optimized to maximize power densities and thermal efficiencies while minimizing tailpipe emissions. Challenges in engineering design include developing flow handling and engine management systems for a commercial-ready device. Lean, premixed combustion is the preferred strategy to control emissions in stationary turbines. It allows for control over the combustion process, but frequently results in acoustic instabilities. Research is needed to develop better control strategies that will help hydrogen and hydrogen-enriched hydrocarbon fuels gain wider acceptance.

In transportation applications, reformer research should be directed to enable near-term end use of hydrogen prior to the development of a nationwide hydrogen delivery system.

Conventional conversion devices need to be demonstrated in stationary, transportation, and hybrid stationary-mobile applications, and should be designed to promote the creation of hydrogen clusters.

For the near term, research is needed to address such issues as durability, cost of the fuel cell stack, system integration, system architecture, and reformer development. The Federal government should designate a lead fuel cell/hydrogen laboratory so that this work is concentrated and available widely. That entity should develop breakthrough technologies and fundamentals that are broadly applicable to all fuel cell applications, while also providing a facility for testing more robust products.

Increase demonstrations significantly. Demonstrations should showcase the near-term availability of multiple alternative technologies for distributed generation power parks. This effort could include the development of hydrogen-based mini economies around an existing hydrogen infrastructure.

Conventional conversion devices need to be demonstrated in stationary, transportation, and hybrid stationary-mobile applications, and should be designed to promote the creation of hydrogen clusters. As the number of demonstration projects grows, so will the hydrogen clusters. This will help jumpstart the creation of the hydrogen infrastructure for both stationary and transportation applications.

Relationships should be built and expanded beyond current demonstration activities. The Federal government could demonstrate stationary fuel cells in government buildings. Numerous partnerships, such as the U.S. Department of Energy's FreedomCAR program and the California Fuel Cell Partnership, have demonstrated the advantages of public-private cooperation for transportation applications. Public-private partnerships to demonstrate early vehicles and the associated fueling infrastructure will be necessary to minimize economic risks.

Institute regulations, codes and standards to foster customer acceptance of the hydrogen vision. Standard nationwide interconnection agreements are needed to enable connection to the current electrical grid without punitive costs, policies, or actions. Standard agreements and educational materials should be prepared for use by fire, insurance, and building code officials.

Develop public policies that encourage use of hydrogen as a fuel.

Convincing Americans to use hydrogen applications will require incentives such as cost-sharing demonstrations, policies for price parity, and "rights-of-way" for hydrogen infrastructure (similar to those in the natural gas industry).

The Federal government should adopt national interconnection standards, require utilities to treat stationary hydrogen customers in a manner similar to others in the same rate class, and ensure that distributed generation options are valued for their ability to utilize waste heat and achieve high efficiencies. Strategies might include development of emissions trading that reaches the small size level, assigning value to externalities via a "carbon tax," or other such measures.

Government could also provide incentives for investing in new technologies, such as tax credits for transportation, stationary, and portable hydrogen systems and for hydrogen infrastructure development.

CONCLUSION

The ultimate aim is to enable consumers to use hydrogen energy devices for transportation, electric power generation in cities and homes, and portable power in

electronic devices such as mobile phones and laptop computers. Once the cost and performance issues associated with hydrogen energy systems have been addressed, the next challenges will involve customer awareness and acceptance. Safety, convenience, affordability, and environmental friendliness are key consumer demands. Industry should focus its efforts on understanding consumer preferences and building them into hydrogen system designs and operations. Government (Federal and State) should identify opportunities to use hydrogen systems in facilities for distributed generation, combined heat and power, and vehicle fleets.

Hydrogen Energy Applications: Needs and Activities

Needs	Activities	Primary Entities
Consensus on technically-based codes and standards	Consortium of agencies to set codes and standards	Federal, State government agencies
Public-private partnership for systems demonstrations	Benchmark California programs demonstration of zero emission vehicle; fuel cell bus fleet demonstration	Federal, State, local government agencies
Government as early adopter	Begin demonstration programs	Federal agencies
Short-term hydrogen end-use technologies to stimulate infrastructure and market readiness	Generate the market with the purchase of fleets	Federal agencies
R&D for onboard storage	Include demos for onboard storage tanks that can achieve 6,7,8% weight of stored hydrogen per weight of tank	Federal agencies, National Laboratories, industry
Community-based clustered applications and installations	Issue RFP, select winners, commence building, complete installations	Federal grants; State and local government and industry cost-share

8 Education and Outreach

INTRODUCTION

Educating consumers, industry leaders, and public policy makers about the benefits of hydrogen is critical to achieving the Vision. The development and implementation of broad-based advocacy and public education programs are critical components of success. Stakeholders lack any real understanding about the development and use of hydrogen: how is it used today; how can it be used in the future; what are the advantages of hydrogen in these new markets; how does hydrogen relate to renewable resources; and what are the storage and safety issues.

Public and private organizations can take a variety of approaches to increase nationwide awareness and acceptance of hydrogen, including coalition building, public relations and media campaigns, community demonstration projects, and long-term commitment of resources to America's education system. To insure success in this arena, consumers will need to understand the value and the relative risks of hydrogen; industry will need to work with other sectors and the media to create consumer demand for hydrogen; and public policy makers will need to develop consistent and sustainable policies and regulations that support hydrogen systems.

The challenge before us is to educate the Nation about the benefits of hydrogen, the relative costs and issues, and the path toward its eventual use as a ubiquitous energy carrier. The message that hydrogen is clean, secure, and safe must be effectively demonstrated to wide and varied audiences. Target audiences include consumers, students, educators, public policy makers, non-governmental organizations, the research and development community, industry, the media, multilateral institutions, and professional and trade associations.

CHALLENGES

A nationwide effort to promote hydrogen faces regulatory and institutional challenges. Common consumer misconceptions about hydrogen as a fuel can impede widespread acceptance of hydrogen. The following are identified as the most pressing issues to be addressed through outreach and education.

The public lacks awareness. Consumers are generally unaware of hydrogen as an energy alternative. Since there is little consensus about the severity of today's environmental problems there is little impetus for change. Hydrogen needs to be "personalized" for consumers so that they understand the value of switching from fossil fuel-based energy systems to hydrogen systems.

Too few examples and success stories exist to lure business investment. Demonstrations of developing technologies are rare, leading to a lack of early adopters willing to invest in new technologies and commercialization. Without demonstrations, technologies remain unproven, consumer demand for new products remains weak, and financing and investment communities are slow to feed the capital pipeline.

Hydrogen education programs are minimal. 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 at all educational levels are not being introduced to

Educating consumers, industry leaders, and public policy makers about the benefits of hydrogen is critical to achieving the Vision.

Target Outreach Audiences

- Consumers (residential, commercial, industrial)
- Students and educators (K-12 and college students, science teachers)
- Federal, state, and local officials/policymakers (including transit agencies, code officials, public utility commissions, state energy offices, and regional planning organizations)
- Non-governmental organizations, foundations, environmental groups, and institutional interests (lenders, investors, insurance, real estate)
- The R&D community
- Industry groups (including industry executives, service station operators and owners, and vehicle fleet operators/owners)
- Multilateral institutions (World Bank, development banks, etc.)
- Professional and trade associations

hydrogen. As a result, students are not stimulated to pursue science and technology careers that support growing business interests, and do not share information about hydrogen and its benefits with their parents and peers.

Policies are inconsistent. Policy makers often are not knowledgeable about hydrogen as a fuel, nor do they understand how it works. Inconsistent regulations at the Federal, state, and local levels—including inconsistent or nonexistent codes and standards—are barriers to the widespread implementation of hydrogen. In addition, existing policies fail to accurately measure the true costs and environmental impacts of our energy choices, thus sending incomplete messages to consumers.

Consumers harbor safety concerns. 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. Fear may also stem from a lack of understanding about the dangers associated with fuels that consumers use today. The following message needs to be communicated: like all fuels, hydrogen can be handled and used safely with appropriate sensing, handling, and engineering measures.

PATHS FORWARD

Specific actions must be taken to overcome the barriers and achieve the vision for a hydrogen economy.

Establish regional, state, and local networks. Networks should be developed to include code officials, building engineers, energy regulators, and consumers in hydrogen technology demonstrations. These networks should provide public education on installation, codes and standards, and safety issues.

Create a broad coalition to influence U.S. energy policy on hydrogen. A hydrogen advocacy coalition could be created to support public policies that encourage the development of hydrogen production, storage, and utilization technologies; the removal of key regulatory and market barriers; the development of education curricula; and the creation of public policies that would make hydrogen an important component of a secure, efficient, and environmentally acceptable energy mix. The coalition could reach out to public and private decision makers regarding the need to implement consistent and sustainable policies and procedures that support hydrogen systems. It could also encourage regional hydrogen initiatives and partnerships, establish informational caucuses, and support a continuous path of technological improvement.

Develop a comprehensive public education and outreach program. Hydrogen needs to get “on the map” and in the minds of consumers. Getting the message out will require a coordinated effort by government, industry, and non-profit communities to develop a broad-based education and outreach program. This program, which should be developed as soon as possible, should include public relations and advertising campaigns. Public spokespersons need to be identified and media briefing

packets produced. A product recognition tag, similar to EnergyStar®, should be developed, and hydrogen success stories should be touted. Other public relations and outreach activities would include:

- Construction of traveling exhibits on hydrogen
- Expansion of online hydrogen databases and information center
- Creation of compact disks and Internet marketing materials

Key components of the education and public relations program include the creation of effective consumer messages, awareness campaigns, and media outreach. Innovative ideas and creative incentives are needed to prime the population for migration toward a hydrogen economy. Consumers need to feel compelled to learn more about hydrogen and must be clear about how a hydrogen economy can benefit the environment and energy security of the Nation.

Hydrogen needs to be “branded” and “personalized” for the consumer; safety needs to be stressed. Messages need to be consistent (e.g., “Hydrogen is the Freedom Fuel,” “Hydrogen—It Works,” or “Hydrogen is ‘The Power’”).

In addition, industry should work with filmmakers to include product placement in movies. Community models and exhibits should also be developed to promote consumer participation and action.

Create a public demonstration hydrogen village. Homebuilders, architects, lending institutions, realtors, technology manufacturers, and related associations should lead an effort to launch a community model or hydrogen village that identifies stakeholders, products, and the infrastructure of a hydrogen economy. Multiple villages, in whole or in part, could be situated in strategic locations across the United States as instructional models for outreach programs directed toward students, government, and industry.

Commit resources for long-term education of students at all levels. Student education is a key component to broadcasting the hydrogen message and developing a knowledgeable, involved hydrogen support network. Without a targeted technology (and applications-level) education program for students and teachers, our past will continue to define our future. Long-term resources should be committed to educate all students. Easy-to-integrate curricula should be developed for kindergarten to grade 12, vocational, four-year engineering, and advanced-degree students. Hydrogen education packages should be created, including lesson plans, videos, demonstration hardware, and experiments to help educate science teachers and their students.

Educator training should be made available to all interested teachers through summer workshops and in-service training. Prizes could be offered for college-level engineering theses and projects on vehicle systems, stationary applications, and storage technologies. In addition, a hydrogen fellowship program should be created to encourage interest in the industry at the graduate-level. Lead organizations for this effort include the National Science Teachers Association, the U.S. Department of Education, education agencies and boards, and textbook publishing companies. This effort should begin immediately with an inventory of educational resources and development of teacher training materials that can be integrated with existing energy education materials.

Key components of the education and public relations program include the creation of effective consumer messages, awareness campaigns, and media outreach.

Hydrogen Themes

- Hydrogen is “The Freedom Fuel”
- Hydrogen provides independence and an environmental choice
- Hydrogen solves foreign oil dependency and improves the environment
- Hydrogen is everywhere—“it’s right in our backyard”
- A hydrogen economy includes other fuels
- Hydrogen—it works (it is an ongoing business today)
- Hydrogen is safe
- Hydrogen is a long-term energy solution
- Hydrogen is the “man on the moon” equivalent for this generation

CONCLUSION

Education and outreach on the many benefits of hydrogen is a vital element of this Roadmap. It will require a long-term, coordinated commitment by diverse stakeholders to effectively communicate key hydrogen messages to a wide and varied audience. A broad-based education and outreach program—including public relations, media campaigns, demonstration activities, and policy initiatives—must start immediately. Education is an ongoing process impacting all aspects of the hydrogen roadmap and its prospects for success.

9 Conclusions

The fundamental purpose of this Roadmap is to define a common set of objectives and activities agreed upon by government, industry, universities, National Laboratories, environmental organizations, and other interested parties. Focusing resources on this common agenda will facilitate evaluation of a hydrogen economy and potentially stimulate investment in the development of a hydrogen energy system.

Strong government-industry partnerships are needed to evaluate the potential for hydrogen to play a larger role in America's energy future. This undertaking requires government leadership and a significant, long-term investment of the Nation's resources, both public and private.

Adoption of hydrogen can be encouraged by policies that reflect the external costs of energy supply, security, air quality, and global climate. These policies must be consistent and provide a clear signal to industry and consumers. A societal dialogue should be initiated to stimulate an informed, ongoing discussion of how we as a society value a low-polluting and diverse energy supply. Although the United States is the focus of this Roadmap, energy markets are global. Over the next several decades, much of the global growth in energy demand is projected to be in developing countries. U.S. efforts in hydrogen technologies can have global benefits.

The widespread use of hydrogen will impact every aspect of the U.S. energy system, from production through end-use. The individual components of a hydrogen energy system—production, delivery, storage, conversion and end-use applications—are closely interrelated and interdependent. The design and implementation of a hydrogen economy must be considered at the “whole system” level.

ELEMENTS OF 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 sequestration. 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” (demand/supply) 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

The fundamental purpose of this Roadmap is to define a common set of objectives and activities agreed upon by government, industry, universities, National Laboratories, environmental organizations, and other interested parties.

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 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.

FINAL THOUGHTS

Development of hydrogen energy technologies represents a potential long-term energy solution with enormous benefits for America. A coordinated and focused effort is necessary to bring public and private resources to bear on evaluating the costs and benefits of the transition to a hydrogen economy. Next steps will include the development of detailed research and development plans for each of the technology areas. A significant commitment of resources—funding, people, and facilities—will be needed to accomplish this. Specifically:

Science and engineering—Challenges are presented in the fundamentals of the materials sciences, electrochemistry, biology, engineering design, and manufacturing. The Federal government, with assistance from State energy agencies and researchers in universities and National Laboratories, has a critical role to play in advancing scientific frontiers. Breakthroughs in hydrogen production, storage, and conversion could alter the assessment of costs and benefits substantially. Greater emphasis needs to be placed on focusing resources on the most promising opportunities. Unproductive research pathways should be terminated. Dissemination of results and the transfer of knowledge to the private sector need to occur at a faster pace and in a more effective manner.

Technology development—An increased level of technical coordination among industry, government, universities, and the National Laboratories is needed to advance hydrogen-related technology development programs in accordance with the activities and priorities put forth in this Roadmap. More specific technology roadmaps need to be developed to attract government and industrial funding to pursue specific technology opportunities, particularly in the areas of hydrogen production, storage, and conversion. The Federal government needs to more closely coordinate activities across several agencies including the Departments of Energy, Transportation, Commerce, and Defense.

Demonstrations—Immediate government-industry coordination is needed in order to implement several types of hydrogen energy technologies — spanning stationary, mobile, and portable applications—to evaluate the potential of hydrogen as an energy solution for America. Technology demonstrations and hydrogen pilot projects can help to uncover problems and compile empirical data to better estimate the costs and benefits of infrastructure requirements for transition to a hydrogen economy. Existing efforts to implement hydrogen fueling stations, power parks, and municipal fleets, for example, should be replicated in a variety of locations and climate conditions. Results should be properly documented and disseminated widely.

Institution building—Energy and environmental policies, utility regulations, business practices, and codes and standards are critical elements of the institutional infrastructure needed to develop hydrogen energy. Public outreach and education programs could inform the public on the ways existing institutions support hydrogen energy development. Policy analysis is needed to identify unnecessary regulatory barriers, and business analysis is needed to identify profitable models for hydrogen energy development (and related concepts such as distributed energy generation and combined heat and power). Efforts to engage code officials in the United States and throughout the world should increase to foster greater harmony and consistency with regard to hydrogen energy products and services.

Implementation of this Roadmap involves making progress on the top priority actions and recommendations. Only by working together—government, industry, universities, National Laboratories, and environmental organizations—will progress be made.

Energy and environmental policies, utility regulations, business practices, and codes and standards are critical elements of the institutional infrastructure in which hydrogen energy needs to develop.



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Available on the U.S. Department of Energy Hydrogen Information Network web site at www.eren.doe.gov/hydrogen:

- Proceedings for the National Hydrogen Vision Meeting
- A National Vision of America's Transition to a Hydrogen Economy—To 2030 and Beyond
- Proceedings for the National Hydrogen Energy Roadmap Workshop
- National Hydrogen Energy Roadmap

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Acronyms

AC	Alternating Current
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ATS	Advanced Turbine Systems
CHP	Combined Heat and Power
CSA	Canadian Standards Association
DC	Direct Current
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
FY	Fiscal Year
ICC	International Codes Council
IEC	Independent Electrical Contractors
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Standards Organization
kW	Kilowatt
NASA	National Aeronautics and Space Administration
PEM	Polymer Electrolyte Membrane
QC	Quality Control
R&D	Research and Development
RFP	Request for Proposal
SAE	Society of Automotive Engineers
SMR	Steam Methane Reformer
SOFC	Solid Oxide Fuel Cell
UL	Underwriters Laboratories, Inc.
V	Volt

