Realizing A Hydrogen Future

Hydrogen Technical Advisory Panel

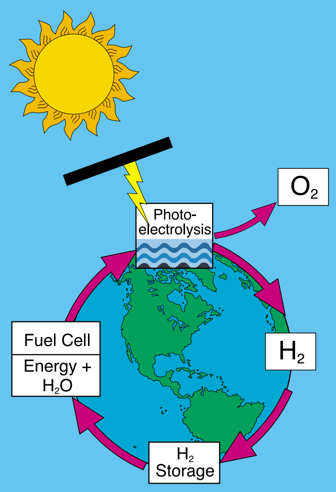
Recommendations

Hydrogen Vision

Strategy

Recommendations

Hydrogen Vision



The hydrogen cycle: when generated from renewable sources, hydrogen production and use is part of a clean, cyclic process.

You don't have to imagine a world in which there is inexhaustible, clean energy. *This* is such a world. The sun is the energy source that, coupled with water, provides electricity, fuel, and heat. And hydrogen is the medium for storing and carrying energy.

Hydrogen — the universe's most abundant element — is part of a clean and elegant cycle: Separate water into hydrogen and oxygen. Use the hydrogen to power a fuel cell, where hydrogen and oxygen from air recombine to produce electrical energy, water, and heat. This process produces no particulates, no carbon dioxide, and no pollution.

Hydrogen may be the perfect energy carrier. Today, it is produced primarily from fossil fuels using well-known commercial thermal processes. In the future, it will be produced directly from water and sunlight.

Today, hydrogen is transported by rail, truck, and pipeline and stored in liquid or gaseous form. In the future, it will be stored and transported in advanced systems, such as metal hydrides or carbon structures.

As a chemical, hydrogen safely provides us with fertilizers, resins, plastics, solvents, and more. As a fuel, it can provide electricity, power our vehicles, and heat our homes and businesses.

Hydrogen can be produced in many ways and from many domestic sources. It offers energy security and diversity for the nation. It expands our technology base to provide America with ample energy choices. And because it is clean, it will promote a healthy environment by reducing or eliminating harmful pollutants.

This is the **vision** of the Hydrogen Technical Advisory Panel and of the DOE Hydrogen Program: *In the 21st century we see the dawning of a new era — toward a clean hydrogen economy that will be based on renewable energy resources.* To realize this vision requires investigating the science, developing the technology, building a safe infrastructure, crafting a robust strategy, and maintaining wise guidance. And it requires a national will.

Hydrogen versatility: hydrogen can be used to generate electricity, heat homes and businesses, fuel our vehicles, and produce commodities we use every day.

Energy Partners, Inc. PIX 02070

Hydrogen proof-of-concept car (1993)

Strategy

NASA, PIX 03988

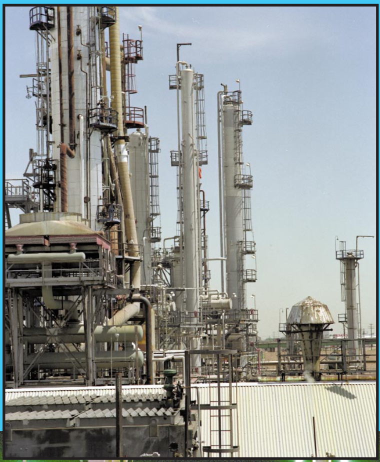
NASA's space shuttle uses liquid hydrogen and oxygen for propulsion and hydrogen-powered fuel cells to provide on-board electricity and water.

Today, the United States safely uses about 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen yearly, almost all of which is produced at oil refineries or by the chemical industry via the steam reforming of natural gas. This hydrogen is used primarily for refining petroleum and for making industrial commodities, such as ammonia.

Comparatively little hydrogen is currently used as fuel or as an energy carrier, i.e., as a medium by which energy may be moved from the place of production to the place of use. Yet, the Hydrogen Program calls for making a transition to a hydrogen-based economy, with the expectation that in the long term hydrogen will join electricity as a major energy carrier and that much of the hydrogen will be derived from renewable energy sources.

Hydrogen Components, Inc., PIX 03548

One of the options for the near term is to mix hydrogen with methane for use in internal combustion engines, as with this "hythane"-fueled pickup.



Today, almost all hydrogen is produced via steam reforming of natural gas at oil refineries. The great majority of that hydrogen is used by oil refineries and petrochemical plants to refine fuel and to make industrial commodities.

Present

Fuel Cells — Options on the Road to a Hydrogen Economy

Fuel cells, which employ hydrogen to produce electricity, can be used to power a wide variety of applications. This is especially true in transportation, where there are several options for providing hydrogen for the fuel cells.

One option for getting the hydrogen is to use an on-board reformer to extract it from the gasoline in our gas tanks. (Reformers break down hydrogen-carbon bonds to produce a mixed gas from which pure hydrogen is derived.) This approach could also be applied to other hydrocarbons, but may require the development of fuel-cell membranes or changes in refining methods.

A second option is to use methanol as the hydrogen carrier. Methanol is easier to reform than gasoline and

Making the Transition

The transition to a hydrogen-based energy economy is being made gradually, in phases, so that by the middle of the 21st century our energy system will be on its way to being clean, renewable, and secure.

Near Term

To expand the role of hydrogen in the *near term*, several approaches are being proposed. One approach is to use hydrogen for transportation by mixing it with natural gas in internal combustion engines; this would increase engine performance and decrease pollution.

Another approach calls for producing hydrogen at central locations and distributing it to refueling stations. There, it will be pumped on board vehicles for use in fuel-cell powered systems. The use of such hydrogen-powered fuel cells produces no emissions other than water vapor, an important element in California's legislative mandate for the introduction of zero-emission vehicles.

Energy crops such as switchgrass (above) or trees (timeline, below) will be used to produce hydrogen in the mid term. The cultivation of these crops will also offset carbon dioxide emissions.

During this near-term phase, hydrogen will be produced primarily by advanced steam reforming of natural gas, either at central or distributed facilities. This presents an opportunity to decrease the amount of carbon dioxide released to the atmosphere — a byproduct of steam reforming is a nearly pure carbon dioxide stream that could be collected and sequestered in many ways, such as coal seams, depleted natural gas fields, or saline aquifers.

Mid Term

In the *mid term*, restructuring of the electric utility industry will present opportunities for distributed generation, where hydrogen-powered fuel cells will provide on-site generation of electricity. In addition to electricity, these fuel cells will

A second near-term option is to use hydrogen-powered fuel cells for transportation.

Near Term

Ballard Power Systems, PIX 01440

California mandates for zero-emission vehicles will provide an opportunity for cars and buses run by hydrogen-powered fuel cells.

can be produced from natural gas, solid fossil fuels, or renewable biomass resources.

A third option is to develop a fuel cell that uses methanol directly, eliminating the need for a separate reformer. Instead, a catalyst on the fuel-cell membrane would chemically break the methanol into hydrogen and carbon dioxide.

A fourth option is to produce the hydrogen at central locations and then store it on board the vehicle as a gas, as a cryogenic liquid, or in a solid. With this option, the hydrogen could be produced via steam reforming of natural gas, via pyrolysis or gasification of biomass or fossil fuels, or via electrolysis of water.

also produce thermal energy for hot water, space heating, and industrial processes.

During this phase, hydrogen for these applications will be increasingly produced from coal and from the pyrolysis or gasification of biomass.

Biomass for hydrogen production will come from dedicated crops, agricultural residues, or municipal solid wastes. Dedicated crops will be particularly valuable for offsetting carbon dioxide emissions because biomass crops regrown specifically for energy recycle carbon dioxide from the atmosphere, resulting in no net carbon dioxide emissions.

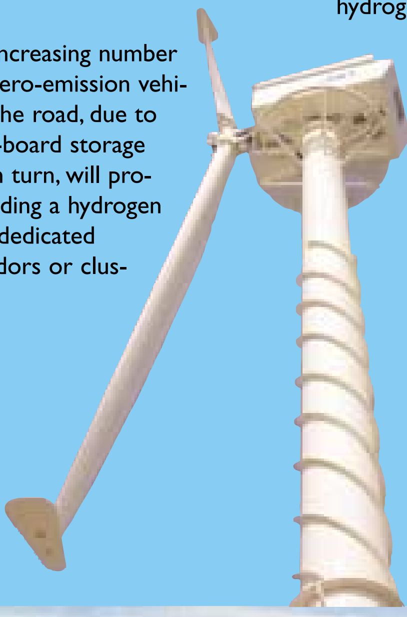
In the mid-term an increasing number of hydrogen-fueled zero-emission vehicles will also be on the road, due to improvements in on-board storage technologies. This, in turn, will provide impetus for building a hydrogen infrastructure along dedicated transportation corridors or clusters of use.

Long Term

In the *long term*, strong hydrogen markets and a growing hydrogen infrastructure will launch opportunities for *renewable* hydrogen systems. Intermittent energy sources such as wind turbines or photovoltaics, for example, will power electrolysis to produce hydrogen for fuel cells. The fuel cells will use the hydrogen to provide electricity during higher demand periods or to supplement the intermittent energy sources.

This era will also witness the emergence and growth of advanced technologies that produce hydrogen from water and sunlight and that store hydrogen in high-energy-density systems.

Market penetration of advanced technologies to produce, store, and use hydrogen will herald the establishment of the hydrogen energy economy.



In the mid to long term, a large and growing renewable-based electric power system will require significant storage capacity — hydrogen will provide a perfect storage medium.

Mid Term

Ballard Power Systems, PIX 02005

Large hydrogen-powered fuel cells will be used in the mid term for distributed electric power applications.

Advanced Hydrogen Technologies

Throughout the transition period, scientists, engineers, and systems designers will advance the technologies for safe hydrogen production, storage, and utilization.

Production Technologies:

- Thermochemical processes — use heat to convert biomass into a gaseous mixture that can produce hydrogen and other valuable products.
- Photobiological processes — use sunlight and the natural activities of enzymes in green algae and bacteria to split water into hydrogen and oxygen.
- Photoelectrochemical processes — use semiconductor technology to split water upon illumination with sunlight.

Storage Technologies:

- Metal hydrides — absorb and retain hydrogen and release it for different applications.
- Carbon nanostructures — contain microscopic pores that adsorb high densities of hydrogen via capillary action at room temperature.

Utilization Technologies:

- Phosphoric acid fuel cells — represent a near-term application for stationary power generation.
- The proton exchange membrane fuel cell (see side bar) — the prime candidate for near- to mid-term applications, especially in automobiles, buses, and light-duty vehicles, and in distributed power applications.
- Solid-oxide and molten carbonate fuel cells — due to their high operating temperatures, have potential for highly efficient combined heat and power applications.

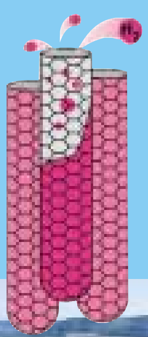
The Hydrogen Program views fuel cell research as a prime avenue for leveraging its funds and expertise, and thus for accelerating the transition timetable. The Program coordinates its efforts with those of a number of other DOE offices, especially Transportation Technologies, Building Technologies, and Fossil Energy. The Program also cooperates with other nations and international organizations, such as the International Energy Agency, where hydrogen and fuel-cell research are being vigorously pursued.

The PEM Fuel Cell

The proton exchange membrane (PEM) fuel cell is a promising option for vehicles and distributed power plants. The cell uses two flow-field plates sandwiched together with a plastic membrane. Hydrogen and air are fed through channels in the plates on either side of the membrane — hydrogen on one side and air on the other. Hydrogen atoms flow through channels to the anode, where they are separated into protons and electrons.

The electrons are conducted through an external circuit, creating a flow of electricity. The protons migrate through the membrane where they combine with oxygen from the air and with electrons from the external circuit; this produces water and heat.

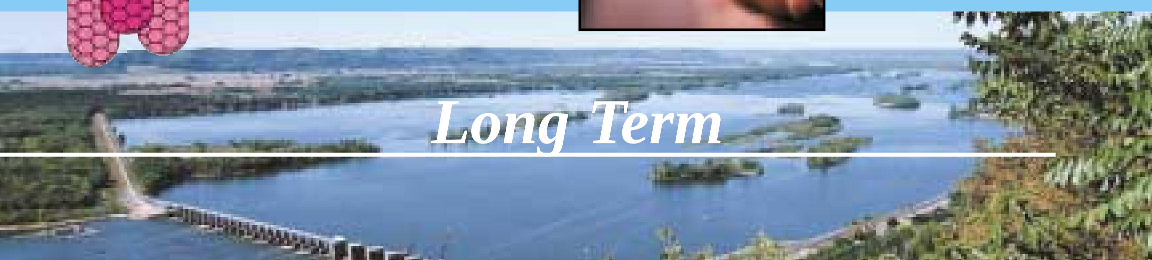
Single cells are combined into a fuel-cell stack to produce the required level of power. In this modular manner, fuel cells can be made to power almost any size application — from laptop computers to cars to entire buildings.



Because of their ability to safely store high volumes of hydrogen and to release the hydrogen on demand by small changes in temperature and pressure, carbon nanostructures (shown schematically) are promising storage options for the long term.

Richard Peterson Photography, Pix 01443

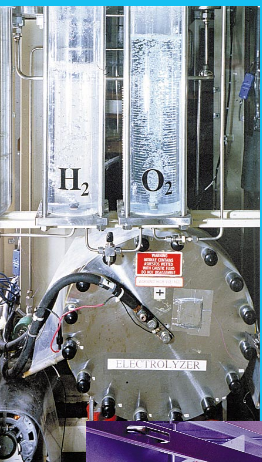
In the long term, advanced technologies, such as this one in which hydrogen and oxygen bubbles are being produced by light shining on a photoelectrochemical device, will be used to produce hydrogen.



Recommendations

The Hydrogen Technical Advisory Panel (HTAP) was created in 1992 in accordance with Section 108 of the Spark M. Matsunaga Hydrogen Research Development and Demonstration Act of 1990 (P.L. 101-566). The Panel's primary functions are to advise the Secretary of Energy on the implementation of the U.S. DOE programs in hydrogen RD&D and to review and make recommendations on the economic, technical, and environmental consequences of deploying safe hydrogen energy systems.

The Matsunaga Act was later amended by the Hydrogen Future Act of 1996 (P.L. 104-271), which authorized additional spending on the research, development, and demonstration of hydrogen production, storage, transport, and use. In addition, this Act requires HTAP to prepare an analysis of the effectiveness of DOE's efforts related to hydrogen and to make recommendations for improvements, including recommendations for future legislation.



From investigating methods for producing and storing hydrogen to analyzing gas streams, maintaining a well-balanced R&D portfolio is essential for realizing the hydrogen vision.

The Panel commends the DOE for —

- devising a balanced strategy for a hydrogen future;
- supporting the mix of technologies being researched and validated;
- making significant progress in these technologies; and
- coordinating hydrogen-related activities within DOE and with other federal agencies.

The Panel recommends strengthening DOE efforts in —

R&D and Technology, by:

- continuing support of a well-balanced portfolio (especially in core R&D) — to ensure realization of the vision and to retain critical capabilities and resources.

Coordination and Outreach, by:

- continuing high-level coordination of hydrogen-related activities across agencies (including DOE, NASA, DOT, DOD, NIST, and other agencies) — to leverage resources, establish a shared knowledge base, and accelerate reaching a hydrogen-powered future.

Legislation and Funding, by:

- extending the Hydrogen Future Act beyond 2001, for five additional years with yearly funding increases — to enable the nation to move more rapidly toward its hydrogen future;
- providing multiyear funding and minimizing funding discontinuities — to increase efficiencies in advancing the technologies and in implementing the Program; and
- supporting hydrogen as an option in federal alternative-fueled vehicle programs — to give this important fuel-cell option, which promises significant societal benefits, the impetus it needs to make a sufficient impact.

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For more information, see the HTAP Website at http://www.eren.doe.gov/hydrogen/htap.htm

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