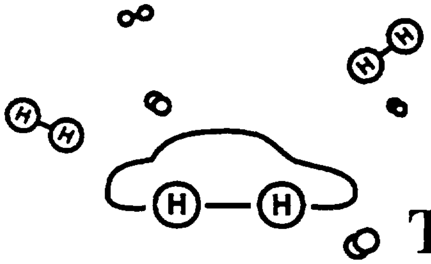
INFORM Strategies for a better environment



Harnessing Hydrogen

The Key to Sustainable Transportation

James S. Cannon

We are living in an era of rapid change in transportation options. Nine years ago, when INFORM began exploring the potential of various alternative transportation fuels, the first hydrogen fuel cell car had not yet been demonstrated. Since then, a number of prototype fuel cell vehicles have been tested. Today's prototypes are costly, and they need refining. But they are, indisputably, a "real world" option.

These new vehicles powered by hydrogen fuel cells offer a glimpse of a radically different personal transportation future — a future powered by renewable and pollution-free energy resources. Along with other fuels and automotive technologies such as electric cars powered by batteries, hydrogen vehicles offer an alternative to our nearly total reliance on oil as a transportation fuel. This alternative offers a solution to the environmental and energy supply problems that, eventually, are sure to undermine the viability of today's conventional cars.

Hydrogen is the key to sustainable transportation because it can be produced in virtually unlimited quantities from renewable resources and because its use is nearly pollution-free.

The major challenge to hydrogen development: Political commitment

The chief challenges to the advancement of hydrogen vehicles are the development of stronger political leadership, heightened national commitment to fundamental change, and the investment of adequate public and private sector financial support. A substantial financial commitment to hydrogen research over the course of a decade would likely lead to the development of a variety of vehicles fueled by hydrogen that perform as well or better than the gasoline vehicles of today, with a small fraction of the environmental impact. This investment in hydrogen would not require "new" federal dollars: A reallocation of funds within our current national energy program (with its emphasis on nuclear and fossil fuels) could finance the move to sustainable transportation.

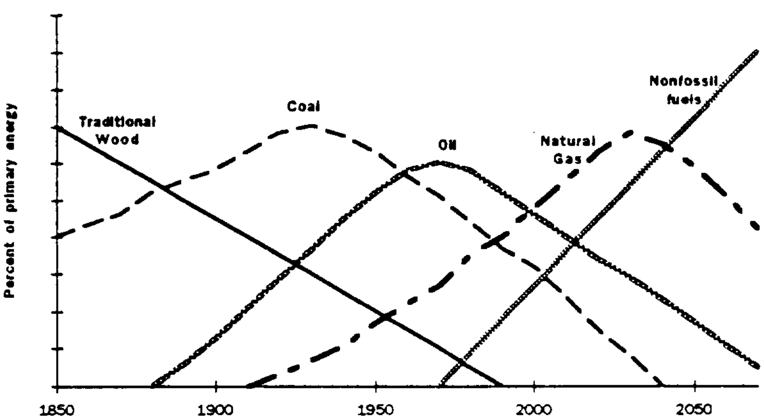
The opportunities for innovation and economic growth in hydrogen energy are largely untapped, and many nations are working to establish an early position in this fledgling field. Germany and Japan are leading the way in hydrogen vehicle technology. There is also growing interest in multinational projects, most of which are proceeding without the participation of the United States.

It remains to be seen what roles various nations will play in providing new automotive fuels and technologies. It is clear, however, that the stakes are huge: in the balance hangs the quality of the environment and the competitiveness of the US automotive and energy industries in the global transportation marketplace of the 21st century.

The transition to new sources of renewable energy

The world is in the middle of the second major energy transition in human history. The first transition occurred when fossil fuels — coal, oil, and natural gas — replaced renewable food and wood resources

Figure 1. Energy Supply Evolution: 1850 – 2050



Source: Adapted from the work of Caesar Marchetti, Austrian International Institute of Applied Systems Analysis, late 1970s

as the major sources of energy used in human activity. This shift to fossil fuels made possible a massive increase in energy use during the past 150 years, which has contributed significantly to the high standard of living enjoyed by industrialized countries.

Table 1. Moving toward Hydrogen: More Powerful, Cleaner Fuels

Fuel Type	Percent Hydrogen	Energy Content (Btu per lb.)	Particulates	Carbon Dioxide
Dry wood	5	6,900	5.22	775
Coal	50	10,000	5.00	240
Oil	67	19,000	0.18	162
Natural Gas	80	22,500	<0.01	117
Hydrogen	100	61,000	0.00	0

INFORM calculations based on energy content and conversion data from US Energy and Information Administration, Annual Energy Review 1993; and I. Ali and M. Basit, "Significance of Hydrogen Content in Fuel Combustion," International Journal of Hydrogen Energy, December 1993; and US EPA, Compilation of Air Pollutant Emission Factors, 1993.

The second energy transition (now in progress) is marked by a transition to cleaner fossil fuels containing less carbon and more hydrogen, a greater reliance on nuclear power, and a shift to renewable resources that humans previously were unable to harness.

Transportation: Severe energy and environmental problems

Harnessing Hydrogen focuses on energy use in the transportation sector because this is an area where the world's energy and environmental problems are particularly severe. Automotive exhaust emissions are the largest single source of air pollution in the world today, especially in urban areas. In the United States, about half of all air pollution regulated under federal law and 31 percent of the carbon dioxide emissions implicated in global warming come from automobiles. The vast majority of the 520 million cars and trucks on the road worldwide burn gasoline or diesel fuel, both of which are refined from oil, the most limited and rapidly depleting fossil fuel.

Hydrogen: Virtually limitless, virtually pollution-free

Hydrogen accounts for more than 80 percent of all the matter in the universe, but most of this hydrogen is bound up in chemical compounds containing other elements. Industry produces hydrogen for a variety of purposes, usually by obtaining it from fossil fuels, the source of more than 99 percent of the hydrogen produced worldwide. Virtually all of this hydrogen is used in the chemical industry as a feedstock; the space program uses a small portion as fuel.

Hydrogen can also be produced using renewable energy resources as part of a sustainable transportation system. For example, solar energy can be used to split the water molecule, releasing hydrogen. Thus produced, pure hydrogen can be burned in an internal combustion engine to power conventional automobiles. Or hydrogen, in a fuel cell, can power an electric vehicle. Either way, using hydrogen releases water vapor as its only by-product. This vapor can serve again as the source of additional hydrogen production, thereby completing a cycle that can be continued indefinitely.

Natural gas: A bridge to hydrogen

The technology for producing and harnessing hydrogen is available today. But establishing a hydrogen-based transportation system would likely take a few decades. Natural gas, a fossil fuel that offers substantial advantages over oil-derived fuels, can also facilitate the transition to hydrogen fuel.

As documented in INFORM's publications, *Drive for Clean Air* and *Paving the Way to Natural Gas Vehicles*, natural gas offers greater energy security compared with gasoline and other transportation fuels because there are abundant natural gas reserves in the United States, Canada, and Mexico. In terms of environmental performance, natural gas vehicles dramatically reduce air pollution: up to 95 percent less carbon monoxide and toxic air pollution, 80 percent fewer hydrocarbon emissions, and 30 percent fewer nitrogen oxides than gasoline. Natural gas vehicles also emit less carbon dioxide, a major contributor to global climate change.

Natural gas already powers about 750,000 vehicles worldwide. As automotive fuels, natural gas and hydrogen are linked in several ways:

- Natural gas and hydrogen can both be burned in internal combustion engines.
- Hydrogen can be added to natural gas to make it burn more cleanly.
- Both fuels share similar automotive storage and refueling system technologies.
- Most manufactured hydrogen is currently extracted from natural gas.
- Some hydrogen could be distributed through existing natural gas pipelines, and the construction of new pipelines to carry hydrogen could benefit from the existing "rights of way" for natural gas distribution.

Because of this overlap, investments to refine and expand the infrastructure for natural gas vehicles can also lay the groundwork for the use of hydrogen.

The essential move to a sustainable transportation system

The first "revolution" in personal transportation occurred at the turn of the last century, with the development of the automobile. Today's electric vehicles, including those powered by fuel cells, represent a second transportation revolution. Alternative fuels — those not derived from oil — have already made inroads in the transportation energy market. By the middle of the 21st century, alternative fuels are destined to become the norm for the world's passenger vehicles. There are four interconnected reasons for this shift:

- Supply: World oil reserves are rapidly diminishing.
- Environment: Pollution from vehicles is creating an atmosphere that is increasingly damaging to public health and the environment.
- Economics: The cost of producing oil and regulating the by-products of oil consumption continues to increase.
- Energy security: The military and political costs of maintaining energy security in international markets are becoming untenable.

Hydrogen: A carrier for renewable energy resources

While this country is pursuing the short-term gains in air quality made possible by reformulated gasoline (at a considerable cost of $37 billion), it must not abandon its aggressive search for renewable energy resources. But if these renewable resources are to power vehicles, they must first be transformed into a clean, movable form, called an "energy carrier." Hydrogen produced from water, using energy from solar resources, may be that optimum energy carrier.

Tapping the sunshine falling on just 5 percent of the world's desert regions would supply enough energy to meet total world energy demand. Five forms of solar energy could be used for hydrogen production:

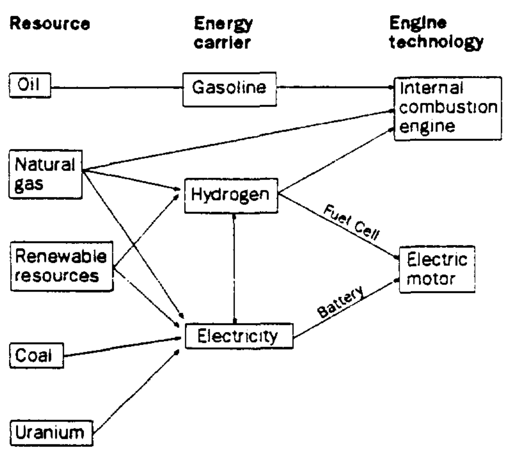
- Solar thermal power: Using the heat from direct sunlight.
- Photovoltaic cells: Converting sunlight to electricity via photosensitive chemicals in the cells.
- Wind power: Tapping wind energy to turn electrical-generating windmills.
- Hydropower: Tapping the energy of falling water, the most widely used renewable energy resource today.

- Biomass: Extracting hydrogen from plant material or burning plant matter to release energy.

Three pathways for hydrogen use in vehicles

Hydrogen has been demonstrated as a viable automotive fuel in three technological modes: internal combustion engines connected mechanically to conventional vehicles; fuel cells that produce electricity to power electric vehicles; and hybrids that involve combinations of engines or fuel cells with electrical storage systems, such as batteries.

Figure 2: Transportation Energy Pathways



This figure demonstrates the versatility of both natural gas and hydrogen. Natural gas can be burned directly in the engine of today's cars; it is also a major fuel for electrical generation and is currently the source of most hydrogen production. Hydrogen is capable of powering both internal combustion engines and electric motors; it can generate electricity and it can be produced directly from renewable resources.

Note: Additional candidates for use in transportation energy systems include other nuclear fuels for fusion reactors and other energy carriers, such as propane, methanol, and ethanol.

Source: INFORM

Using hydrogen in internal combustion engines

Conventional combustion engines require modification, not major redesigning, to burn hydrogen. The proven, commercially available technology to use natural gas in combustion engines is similar to the technology needed to use hydrogen.

Burning hydrogen releases less pollution than burning any fossil fuel. Hydrogen combustion releases no carbon monoxide, hydrocarbons, particulate pollution, or carbon dioxide. The most significant environmental challenge associated with hydrogen combustion is the emission of nitrogen oxides, formed when heat from combustion causes nitrogen and oxygen in the air to fuse. These emissions are very low, however, and they could be further reduced using pollution control equipment.

Demonstration projects have shown that a natural gas blend containing 5 percent hydrogen reduces air pollution from natural gas vehicles by 50 percent and provides a practical way to introduce hydrogen as an automotive fuel.

Using hydrogen in fuel cells

Hydrogen and oxygen merge in a fuel cell, forming water and releasing energy as electricity. Because fuel cells require no lubricating oil, and because there is no combustion to generate the high temperatures that lead to the formation of nitrogen oxides, fuel cell-powered electric vehicles offer the cleanest way of using hydrogen: they are zero-emission vehicles.

Fuel cells are two to three times as energy efficient as combustion engines. An internal combustion engine loses more than 80 percent of the energy it generates, either as waste heat or friction. When a hydrogen fuel cell is used, the energy loss is 40 to 60 percent, so the percent of energy that is delivered as movement is much greater.

Various technological hurdles must be overcome before fuel cells can compete effectively, in terms of overall performance and cost, with internal combustion engines in automotive applications. Fuel cell demonstration projects now under way around the world will likely yield improved solutions to these technical challenges.

Hydrogen electric hybrids

By combining onboard engines or fuel cells that generate power with electrical systems that store power, electric hybrids may offer greater market potential than vehicles powered solely by single systems. Demonstrations of hybrid technology involving hydrogen indicate that these vehicles may be lighter, smaller, more versatile, and offer better performance than vehicles running solely on hydrogen engines, fuel cells, or batteries.

A comparison of fuels cells and batteries

Fuel cells and batteries offer alternative ways of delivering electricity to an electric vehicle. Batteries store electricity, previously generated by an outside source, in the form of chemical energy. In contrast, fuel cells actually generate electricity on board the vehicle.

The electric motor, controller, and many of the other components for electric battery-powered vehicles are identical to the systems used in hydrogen fuel cell vehicles. However, hydrogen offers certain advantages over batteries. For example, refueling with hydrogen is quicker than recharging batteries, and hydrogen storage systems are much lighter and smaller than batteries.

Hydrogen vehicles over the years

Until recently, nearly all of the hydrogen-powered vehicles in use have run on modified internal combustion engines. The earliest testing of hydrogen in internal combustion engines dates back to the late nineteenth century. In Germany before World War II, more than a thousand vehicles were modified to run on hydrogen.

In the aftermath of the 1973 oil embargo, dozens of prototype internal combustion vehicles were built in the United States, Europe, and Japan to run on hydrogen. These hydrogen programs continue, with many automakers testing hydrogen vehicles. Fuel cell and electric hybrid vehicles are a much more recent phenomenon: the first fuel cell demonstration vehicles took to the road in 1993.

Options for producing, distributing, and storing hydrogen

Aside from the propulsion system itself, there are other factors affecting the commercialization of hydrogen vehicles, including fuel production, distribution to refueling stations, and storage on board the vehicle.

Producing hydrogen

Most hydrogen produced today is made from natural gas in a process known as steam reforming. Because this is the cheapest and most firmly established method of producing hydrogen, it is likely to predominate until production technologies based on renewable energy resources become commercially competitive. All of the methods of producing hydrogen from renewable resources face technical and economic hurdles that must be overcome if hydrogen is to fuel a sustainable transportation economy.

Nonetheless, within a decade, applied research could allow each of the following methods to play a vital role in producing commercial quantities of hydrogen. The first two methods listed below use highly developed technology, while the latter three are still in the early stages of development.

- Using electricity from renewable resources, such as hydropower, to split the water molecule through electrolysis.
- Converting organic matter into hydrogen through the gasification processes of partial oxidation, pyrolysis, and steam reforming.
- Using sunlight to heat catalysts that trigger the splitting of water into hydrogen and oxygen.
- Collecting hydrogen generated as a waste product by some strains of algae and bacteria.
- Heating water to more than 5,600 degrees Fahrenheit to break the molecular bonds and make it decompose into its constituent parts.

Distributing hydrogen

Once produced, hydrogen must be transported to markets. Today's hydrogen distribution system is extremely limited: there are only 450 miles of hydrogen pipeline in the United States, compared with

200,000 miles of oil pipeline and 1.3 million miles of natural gas pipeline.

Nonetheless, hydrogen pipeline distribution is a firmly established technology. The key obstacle to making the fuel widely available is the scale of expansion needed to serve transportation markets.

Another option is to liquefy hydrogen for distribution via barges, tankers, and rail cars. This is how liquefied hydrogen is delivered to its main customer, the space program.

Storing hydrogen

Storing hydrogen on board a vehicle raises three critical issues: the weight of the fuel storage system, the system's volume, and the speed or ease of refueling the vehicle. These limitations can be minimized if hydrogen is used in fuel cells, because fuel cells' inherently high efficiency reduces the amount of fuel a vehicle must carry. In contrast, the greater amount of fuel needed to power a hydrogen internal combustion engine vehicle makes these vehicles somewhat less practical.

The natural gas–hydrogen continuum

The technology and infrastructure to produce, store, and distribute natural gas overlaps significantly with those needed for hydrogen. For this reason, the present and expanded use of natural gas as a vehicle fuel should ease the entry of hydrogen into the US energy market.

In theory, natural gas could be transported via pipeline in a blend containing up to 20 percent hydrogen, offering a cleaner fuel without modifying natural gas pipelines. However, modifying the same pipelines to carry pure hydrogen would require further research to address a number of differences between the two fuels. Similarly, the experience gained by transporters of liquefied natural gas would also be an asset as the market for shipping liquefied hydrogen grows.

Harnessing Hydrogen draws many connections between the systems to use natural gas and hydrogen in vehicles. For example:

The environmental impact and safety of hydrogen fuel

From production to distribution to end use, hydrogen fuel cycles are generally cleaner than the gasoline fuel cycle. And hydrogen offers some safety advantages over gasoline.

Producing hydrogen from renewable resources and using it in a fuel cell vehicle eliminates all air pollution associated with the fuel cycle. The major environmental consideration during the production and distribution of hydrogen from most renewable resources is the large land area required by solar technologies. Producing hydrogen from natural gas, although not pollution-free, results in only a fraction of the environmental impact associated with the gasoline fuel cycle.

All fuels, including hydrogen, pose significant safety hazards, but the widely held public perception of hydrogen as an especially dangerous fuel is largely a myth. In reality, hydrogen has compiled an excellent safety record throughout decades of use in the space program. Nonetheless, hydrogen vehicles have not yet been widely used under "real-world" driving conditions. To ensure that they are handled in a safe manner, certain characteristics of hydrogen must be addressed. Technological solutions to these safety challenges are either available or under development.

- The weight and volume of hydrogen fuel storage systems needed in fuel cell-powered vehicles are comparable with the weight and volume of the systems used successfully in natural gas vehicles.
- The materials and systems used to refuel natural gas vehicles are analogous to those used to refuel hydrogen-powered vehicles. For hydrogen-natural gas mixtures, they are the same as for natural gas.
- "Fast-fill" compressed-gas refueling technology can be adapted from natural gas systems and used to fill hydrogen fuel cell vehicles, offering a refueling time of about 5 minutes, which is comparable to gasoline refueling today.
- Natural gas and hydrogen both offer greater energy density in liquefied form than in gaseous form — reducing the space requirements of fuel storage by half, when compared with compressed gas.

Hydrogen development in the United States

Interest in hydrogen as a fuel has grown dramatically in the United States since 1990. The $10 million federal research and development program for hydrogen technologies, although still minuscule compared with other energy development efforts, has increased 10 times since the beginning of the decade. In 1995, spending by the United States government was surpassed only by that of the Japanese government ($23 million) and the German government ($12 million).

At the same time, promising state, local, and private entrepreneurial hydrogen development efforts are under way. *Harnessing Hydrogen* describes these innovative research and development projects, from the first company to demonstrate a fuel cell vehicle to the most ambitious municipal programs to curb urban air pollution using hydrogen vehicles.

Federal hydrogen programs: Limited budgets, fragmented leadership

Despite the increase in hydrogen-related activities in the United States, the total effort by the federal government is still too small to spur sufficient private sector involvement in hydrogen technology or to catalyze a move toward a sustainable transportation system based on hydrogen. Annual federal spending on petroleum research is still 90 times greater than the national hydrogen budget. Hydrogen spending also pales in comparison with government investments in other innovative transportation technologies.

The multidimensional nature of transportation energy issues requires strong leadership to ensure that all federal programs are moving in concert toward a common goal. The space program enjoyed such leadership, coordination, and national commitment. To date, these are lacking with regard to sustainable transportation in general and hydrogen vehicle development in particular.

A redirection of funding priorities could stimulate a competitive environment for the commercial development of the new hydrogen-based transportation technologies. At the same time, a greater focus on hydrogen vehicles could improve the United States' position in fast-changing international automotive and energy markets. While the US vehicle market is nearly saturated, China has one vehicle per 652 people; in India that ratio is 1 to 354. Because

Figure 3: Major Federal, State, and Local Hydrogen Research and Development Activities

National Hydrogen Program
Activities administered by the Department of Energy Office of Utility Technologies
- Hydrogen storage
- Hydrogen fuel production
- Development and demonstrations of hydrogen in vehicles and utility and industrial applications
- Analyses of hydrogen fuel cycle energy efficiency, safety, and transportation and fueling infrastructure

National Fuel Cells in Transportation Program
Activities administered by the Department of Energy Office of Transportation Technologies
- Heavy-duty hydrogen fuel cell engine development
- Fuel-cell-powered passenger vehicle development
- Onboard steam reforming of methanol to hydrogen
- Onboard hydrogen storage

South Coast Air Quality Management District (CA)
- DOE-sponsored phosphoric acid fuel cell bus
- Proton-exchange membrane (PEM) fuel cell
- Production of solar-generated hydrogen, operation of refueling station, and vehicle demonstrations
- Pickup trucks running on solar-generated hydrogen

City of Palm Desert (CA)
- Renewable hydrogen production and use in PEM fuel-cell-powered golf carts

City of Palm Springs (CA)
- Demonstration of eight-passenger PEM fuel cell shuttle vehicle for use at regional airport

Denver Department of Health and Hospitals (CO)
- Demonstration of pickup trucks converted to run on natural gas mixed with hydrogen

New York State Energy Research and Development Authority
- Carbon adsorbent hydrogen storage technology
- PEM fuel cell for hybrid electric bus
- PEM fuel cell for high-speed and low-cost manufacture

Pennsylvania Energy Office
- Converted car to run with PEM fuel cell engine
- Tests of natural gas/hydrogen mixture in van

they have little or no economic investment in the conventional automotive infrastructure, countries now building personal transportation systems from the ground up are likely to look to cleaner alternative fuels and engine technologies to avoid the problems associated with oil use.

Hydrogen development worldwide: Will the United States compete?

Except for space travel applications, world leadership in hydrogen research has never been centered in the United States. Today, Japan and Germany are better poised than the United States to capitalize on the nascent market opportunities for hydrogen-powered vehicles.

Both Germany and Japan have made a national commitment to developing hydrogen as an alternative to oil dependence. In recent years, Japan's hydrogen development effort has eclipsed that of Germany: Japan has committed itself to a 28-year, $11 billion program.

Major automakers in both countries are playing a significant role in hydrogen development: Germany's Mercedes Benz and BMW and Japan's Mazda have all produced advanced prototype vehicles. These companies' work, described in *Harnessing Hydrogen*, includes designing and demonstrating hydrogen vehicles as well as researching liquefied hydrogen and metal hydride storage systems.

Harnessing Hydrogen also describes hydrogen development efforts in other countries, including Belgium, Canada, Ireland, Italy, Norway, and Saudi Arabia. Canada makes and consumes more hydrogen per capita than any other nation, and its program is oriented toward serving world energy markets with hydrogen produced from its vast natural gas and hydropower resource base. Canada, Norway, and Saudi Arabia are each participating in multinational projects that aim to link hydrogen energy-producing regions with countries that have high levels of energy consumption.

Around the globe, interest in hydrogen fuel is growing rapidly, and so is competition to develop the technologies needed to make its widespread use a reality. The actions that US policymakers and business leaders take now will determine what role the United States will play in the hydrogen energy systems of the future.

About INFORM

INFORM is a national nonprofit environmental research organization that examines business and government practices that threaten our environment and public health; assesses changes business and government are making to improve their performance; and identifies new business strategies and technologies moving the United States toward an environmentally sustainable economy. INFORM's research focuses on strategies to prevent industrial and municipal waste and to preserve air and water quality.

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Paving the Way to Natural Gas Vehicles (James S. Cannon), 1993, 192 pages, $25.

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