

► Will motorists someday fill up their tanks with hydrogen? Many complex challenges must be overcome before a hydrogen-fueled future can become a reality.

# High Hopes for

Using hydrogen to fuel cars may eventually slash oil consumption and carbon emissions, but it will take some time **BY JOAN OGDEN**

Developing cleaner power sources for transportation is perhaps the trickiest piece of the energy puzzle. The difficulty stems from two discouraging facts. First, the number of vehicles worldwide, now 750 million, is expected to triple by 2050, thanks largely to the expanding buying power of customers in China, India and other rapidly developing countries. And second, 97 percent of transportation fuel currently comes from crude oil.

In the near term, improving fuel economy is the best way to slow the rise in oil use and greenhouse gas emissions from cars and trucks. But even if automakers triple the efficiency of their fleets and governments support mass transit and smart-growth strategies that lessen the public's reliance on cars, the explosive growth in the number of vehicles around the world will severely limit any reductions in oil consumption and carbon dioxide emissions. To make deeper cuts, the transportation sector needs to switch to low-carbon, nonpetroleum fu-

els. Liquid fuels derived from woody plants or synthesized from tar sands or coal may play important roles. Over the long term, however, the most feasible ways to power vehicles with high efficiency and zero emissions are through connections to the electric grid or the use of hydrogen as a transportation fuel.

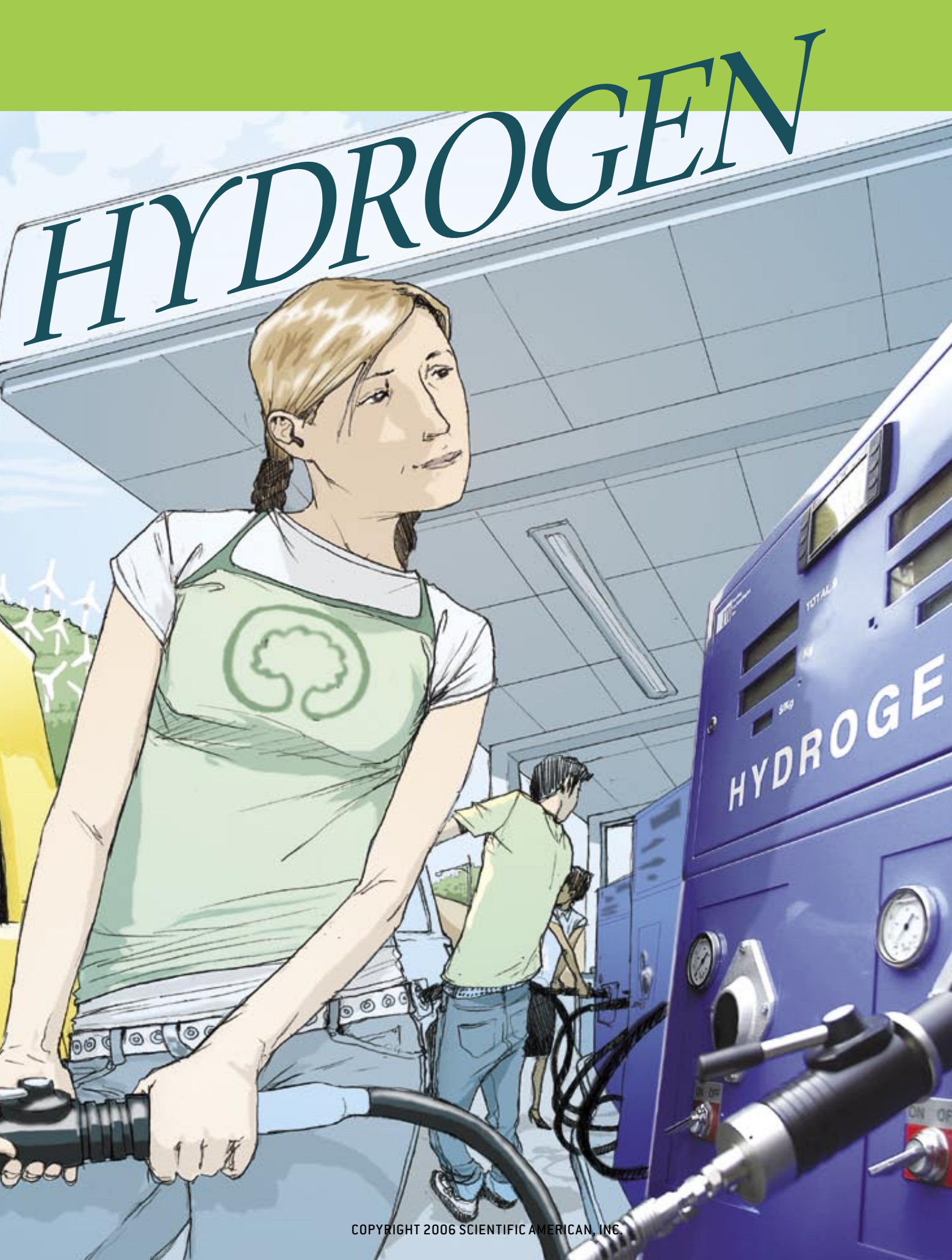
Unfortunately, the commercialization of electric vehicles has been stymied by a daunting obstacle: even large arrays of batteries cannot store enough charge to keep cars running for distances comparable to gasoline engines. For this reason, most auto companies have abandoned the technology. In contrast, fuel-cell vehicles—which combine hydrogen fuel and oxygen from the air to generate the power to run electric motors—face fewer technical hurdles and have the enthusiastic support of auto manufacturers, energy companies and policymakers. Fuel-cell vehicles are several times as efficient as today's conventional gasoline cars, and their only tailpipe emission is water vapor.

## OVERVIEW

\* Hydrogen fuel-cell cars could become commercially feasible if automakers succeed in developing safe, inexpensive, durable models that can travel long distances before refueling.

\* Energy companies could produce large amounts of hydrogen at prices competitive with gasoline, but building the infrastructure of distribution will be costly.

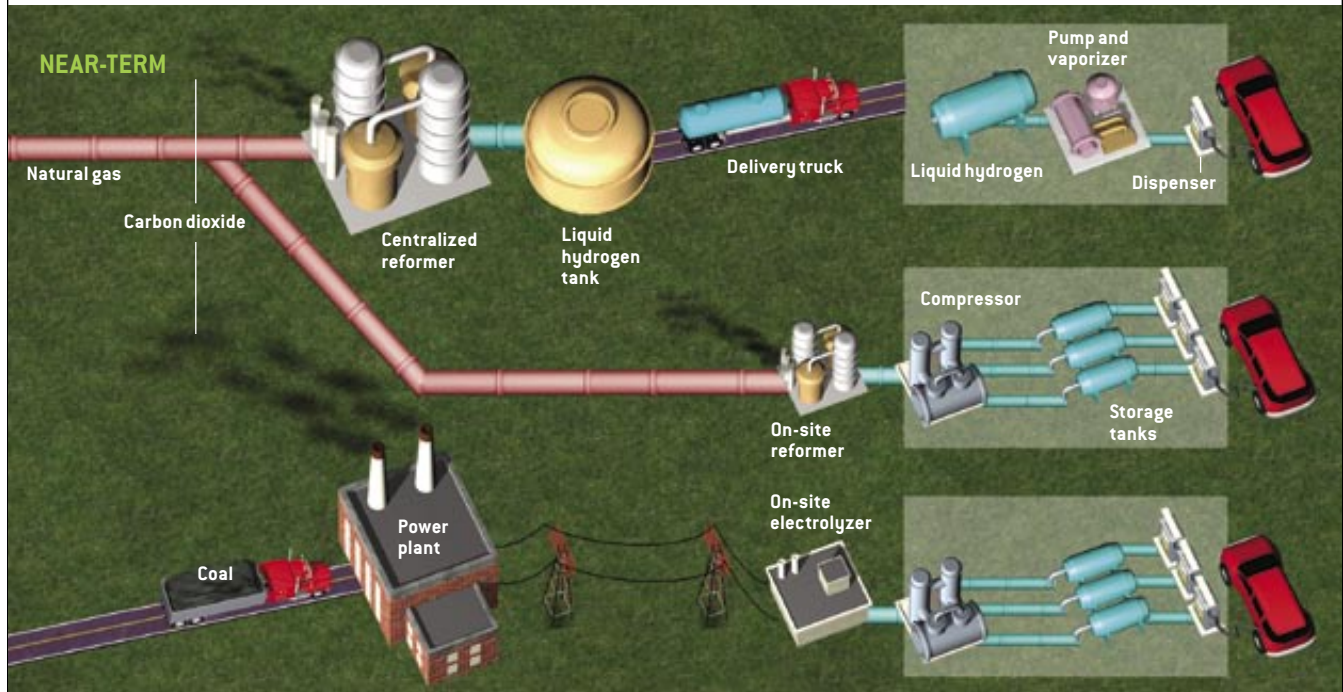
MATT VINCENT ILLUSTRATION; JOE RAEDLE Getty Images (photograph)



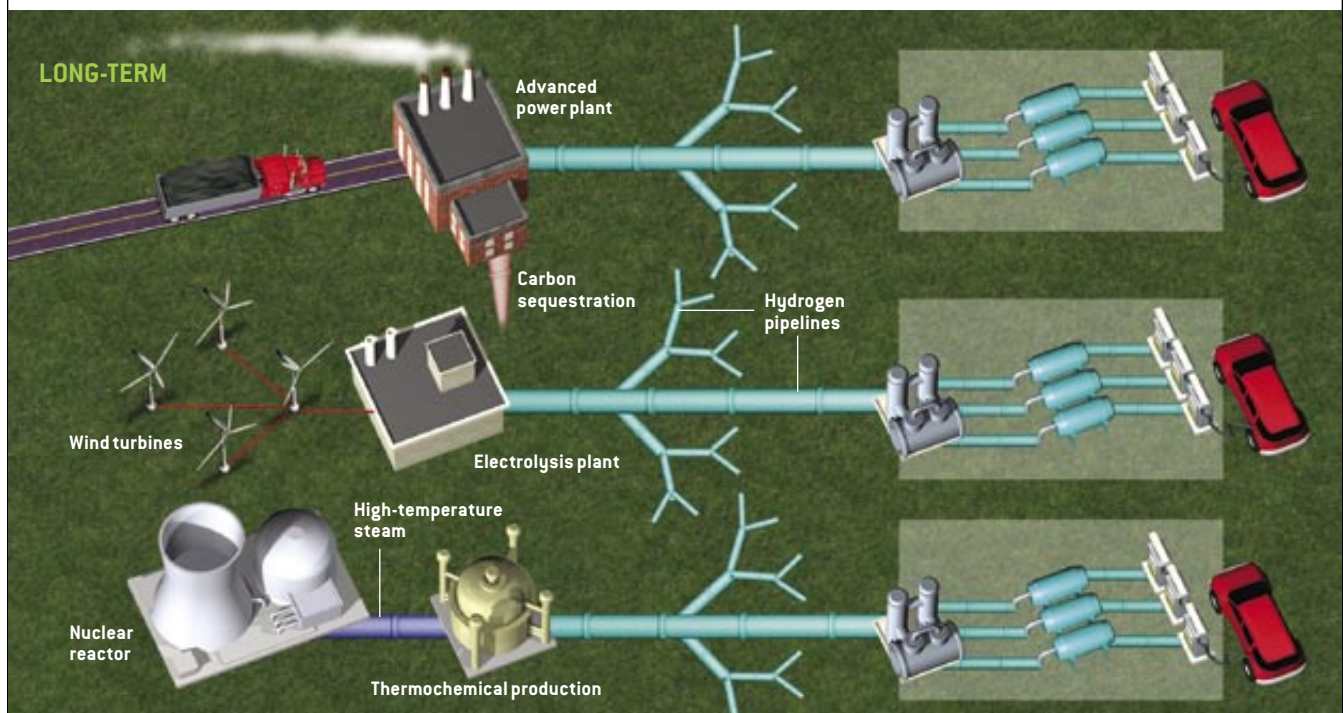
# HYDROGEN

# OPTIONS FOR A HYDROGEN INFRASTRUCTURE

Energy companies could manufacture and distribute hydrogen fuel in many ways. In the near term, the most likely option is extracting hydrogen from natural gas, either in centralized reformers that supply fueling stations by delivery truck or in smaller on-site reformers located at the stations. The fueling stations could also use electricity from the power grid to make hydrogen by electrolyzing water. All these options, however, would produce greenhouse gas emissions (assuming that fossil fuels are used to make the electricity).



In the long term, policymakers should encourage cleaner methods. Advanced power plants could extract hydrogen from coal and bury the carbon dioxide deep underground. Wind turbines and other renewable energy sources could provide the power for electrolysis. And high-temperature steam from nuclear reactors could generate hydrogen through the thermochemical splitting of water.



DON FOLEY

What is more, hydrogen fuel can be made without adding any greenhouse gases to the atmosphere. For example, the power needed to produce hydrogen from electrolysis—using electricity to split water into hydrogen and oxygen—can come from renewable energy sources such as solar cells, wind turbines, hydroelectric plants and geothermal facilities. Alternatively, hydrogen can be extracted from fossil fuels such as natural gas and coal, and the carbon by-products can be captured and sequestered underground.

Before a hydrogen-fueled future can become a reality, however, many complex challenges must be overcome. Carmakers must learn to manufacture new types of vehicles, and consumers must find them attractive enough to buy. Energy companies must adopt cleaner techniques for producing hydrogen and build a new fuel infrastructure that will eventually replace the existing systems for refining and distributing gasoline. Hydrogen will not fix all our problems tomorrow; in fact, it could be decades before it starts to reduce greenhouse gas emissions and oil use on a global scale. It is important to recognize that a hydrogen transition will be a marathon, not a sprint.

## The Fuel-Cell Future

OVER THE PAST DECADE, 17 countries have announced national programs to develop hydrogen energy, committing billions of dollars in public funds. In North America more than 30 U.S. states and several Canadian provinces are developing similar plans. Most major car companies are demon-

strating prototype hydrogen vehicles and investing hundreds of millions of dollars into R&D efforts. Honda, Toyota and General Motors have announced plans to commercialize fuel-cell vehicles sometime between 2010 and 2020. Automakers and energy companies such as Shell, Chevron and BP are working with governments to introduce the first fleets of hydrogen vehicles, along with small refueling networks in California, the northeastern U.S., Europe and China.

reational or business purposes. During periods of peak power usage, when electricity is most expensive, fuel-cell cars could also act as distributed generators, providing relatively cheap supplemental power for offices or homes while parked nearby. Automakers, however, must address several technical and cost issues to make fuel-cell cars more appealing to consumers. A key component of the automotive fuel cell is the proton-exchange membrane (PEM), which separates the hydrogen fuel from the oxygen. On one side of the membrane, a catalyst splits the hydrogen atoms into protons and electrons; then the protons cross the membrane and combine with oxygen atoms on the other side. Manufacturers have reduced the weight and volume of PEM fuel cells so that they easily fit inside a compact car. But the membranes degrade with use—current automotive PEM fuel cells last only about 2,000 hours, less than half the 5,000-hour lifetime needed for commercial vehicles. Companies are developing more durable membranes, however, and in late 2005 researchers at 3M, the corporation best known for Scotch tape and Post-it notes, reported new designs that might take fuel cells to 4,000 hours and beyond within the next five years.

Another big challenge is reducing the expense of the fuel cells. Today's fuel-cell cars are handmade specialty items that cost about \$1 million apiece. Part of the reason for the expense is the small scale of the test fleets; if fuel-cell cars were mass-produced, the cost of their propulsion systems would most likely drop to a more manageable \$6,000 to \$10,000. That price is equivalent to \$125 per kilowatt of engine power,

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strating prototype hydrogen vehicles and investing hundreds of millions of dollars into R&D efforts. Honda, Toyota and General Motors have announced plans to commercialize fuel-cell vehicles sometime between 2010 and 2020. Automakers and energy companies such as Shell, Chevron and BP are working with governments to introduce the first fleets of hydrogen vehicles, along with small refueling networks in California, the northeastern U.S., Europe and China.

The surge of interest in hydrogen stems not only from its long-term environmental benefits but also from its potential to stimulate innovation. Auto manufacturers have embraced fuel-cell cars because they promise to become a superior consumer product. The technology offers quiet operation, rapid acceleration and low maintenance costs. Replacing internal-combustion engines with fuel cells and electric motors eliminates the need for many mechanical and hydraulic subsystems; this change gives automakers more flexibility in designing these cars and the ability to manufacture them more efficiently. What is more, fuel-cell vehicles could provide their owners with a mobile source of electricity that might be used for rec-

which is about four times as high as the \$30-per-kilowatt cost of a comparable internal-combustion engine. Fuel cells may require new materials and manufacturing methods to reach parity with gasoline engines. Car companies may also be able to lower costs by creatively redesigning the vehicles to fit the unique characteristics of the fuel cell. GM officials have stated that fuel-cell cars might ultimately become less expensive than gasoline vehicles because they would have fewer moving parts and a more flexible architecture.

Automobile engineers must also figure out how to store enough hydrogen in a fuel-cell car to ensure a reasonable driving range—say, 300 miles. Storing hydrogen in its gaseous state requires large, high-pressure cylinders. Although liquid hydrogen takes up less space, it must be supercooled to temperatures below  $-253$  degrees Celsius ( $-423$  degrees Fahrenheit). Automakers are exploring the use of metal hydride systems that adsorb hydrogen under pressure, but these devices tend to be heavy (about 300 kilograms). Finding a better storage method is a major thrust of hydrogen R&D worldwide. In the absence of a breakthrough technology, most fuel-cell ve-

hicles today opt for the simplicity of storing the hydrogen as a compressed gas. With clever packaging and increased pressure, these cars are approaching viable travel ranges without compromising trunk space or vehicle weight. In 2005 GM, Honda and Toyota demonstrated compact fuel-cell cars with a 300-mile range using hydrogen gas compressed at 70 megapascals. (Atmospheric pressure at sea level is about 0.1 megapascal.)

Finally, safety is a necessary precondition for introducing any new fuel. Although hydrogen is flammable, it has a higher ignition temperature than gasoline and disperses in the air much more quickly, reducing the risk of fire. On the downside, a much wider range of concentrations of hydrogen is flammable, and a hydrogen flame is barely visible. Oil refineries, chemical plants and other industrial facilities already handle vast quantities of hydrogen without incident, and with proper engineering it can be made safe for consumer applications as well. The U.S. Department of Energy and other groups are currently developing safety codes and standards for hydrogen fuel.

Once hydrogen cars are introduced, how soon could they capture a large share of the market and start to significantly reduce carbon emissions and oil use? Because cars last about 15 years, it would take at least that long to switch over the entire fleet. Typically after a new automotive technology un-

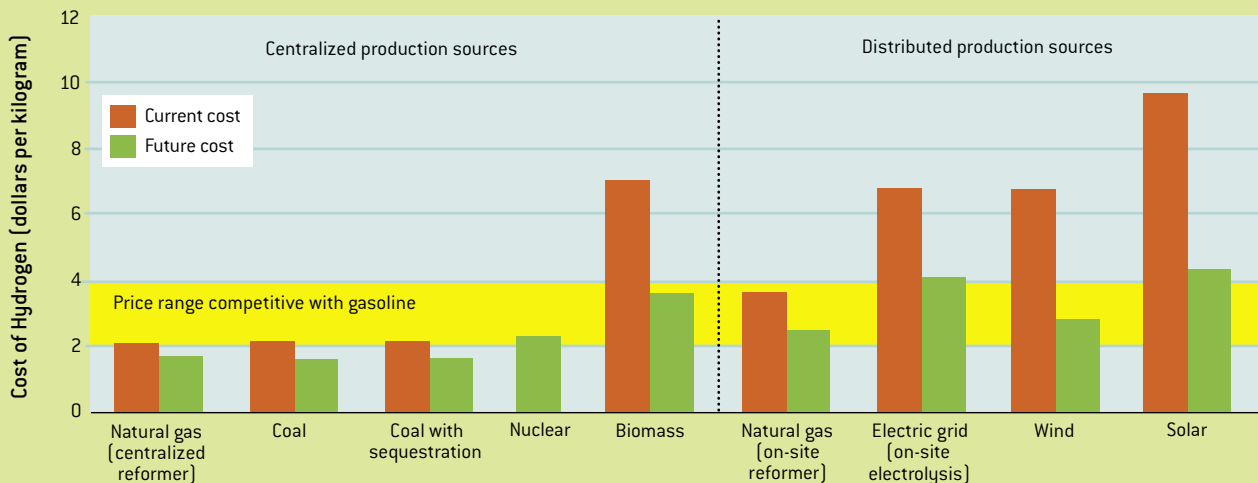
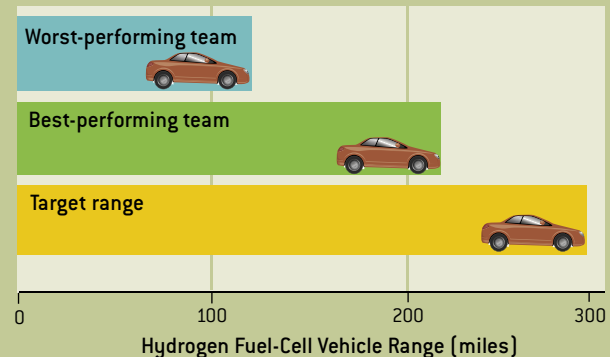
dergoes precommercial research, development and demonstration, it is introduced to the market in a single car model and only later appears in a variety of vehicles. (For example, hybrid gas-electric engines were first developed for compact sedans and later incorporated into SUVs.) Costs generally fall as production volumes increase, making the innovation more attractive. It can take 25 to 60 years for a new technology to penetrate a sizable fraction of the fleet. Although fundamental research on hybrid vehicles began in the 1970s, it was not until 1993 that Toyota began development of the Prius hybrid. Initial sales began in late 1997, but eight years later hybrid models from several manufacturers still accounted for only 1.2 percent of new vehicle sales in the U.S.

### Harvesting Hydrogen

LIKE ELECTRICITY, hydrogen must be produced from some energy source. Currently the vast majority of hydrogen is obtained from the high-temperature processing of natural gas and petroleum. Oil refineries use hydrogen to purify petroleum-derived fuels, and chemical manufacturers employ the gas to make ammonia and other compounds. Hydrogen production now consumes 2 percent of global energy, and its share is growing rapidly. If all this hydrogen were devoted to

## HURDLES FOR HYDROGEN

One of the challenges facing fuel-cell cars is extending their range. The U.S. Department of Energy's National Renewable Energy Laboratory recently measured the ranges of 59 fuel-cell cars made by four industry teams (right). Even the best-performing team fell short of the 300-mile range needed for a commercial vehicle. Another challenge is lowering the price of hydrogen fuel. Making hydrogen from renewable energy sources such as wind, solar and biomass power is currently too expensive, but future technologies could make zero-emissions production more affordable (below).



JEN CHRISTIANSEN; SOURCES: NATIONAL RENEWABLE ENERGY LABORATORY (vehicle ranges); NATIONAL RESEARCH COUNCIL AND NATIONAL ACADEMY OF ENGINEERING (hydrogen prices); JANET CHAO (cars)

fuel-cell cars, it would power about 150 million vehicles, or about 20 percent of the world's fleet. Although most hydrogen is produced and immediately used inside refineries or chemical plants, some 5 to 10 percent is delivered to distant locations by truck or pipeline. In the U.S. this delivery system carries enough energy to fuel several million cars, and it could serve as a springboard to a hydrogen economy.

Making hydrogen from fossil fuels, however, generates carbon dioxide as a by-product. If hydrogen were produced from natural gas, the most common method today, and used in an efficient fuel-cell car, the total greenhouse gas emissions would work out to be about 110 grams per kilometer driven. This amount is somewhat less than the total emissions from a gasoline hybrid vehicle (150 grams per kilometer) and significantly less than those from today's conventional gasoline cars (195 grams per kilometer).

The ultimate goal, though, is to produce hydrogen with little or no greenhouse gas emissions. One option is to capture the carbon dioxide emitted when extracting hydrogen from fossil fuels and inject it deep underground or into the ocean. This process could enable large-scale, clean production of hydrogen at relatively low cost, but establishing the technical feasibility and environmental safety of carbon sequestration will be crucial. Another idea is biomass gasification—heating organic materials such as wood and crop wastes so that they release hydrogen and carbon monoxide. (This technique does not add greenhouse gases to the atmosphere, because the carbon emissions are offset by the carbon dioxide absorbed by the plants when they were growing.) A third possibility is the electrolysis of water using power generated by renewable energy sources such as wind turbines or solar cells.

Although electrolysis and biomass gasification face no major technical hurdles, the current costs for producing hydrogen using these methods are high: \$6 to \$10 per kilogram. (A kilogram of hydrogen has about the same energy content as a gallon of gasoline, but it will propel a car several times as far because fuel cells are more efficient than conventional gasoline engines.) According to a recent assessment by the National Research Council and the National Academy of Engineering, however, future technologies and large-scale production and distribution could lower the price of hydrogen at the pump to \$2 to \$4 per kilogram [see box on opposite page]. In this scenario, hydrogen in a fuel-cell car would cost less per kilometer than gasoline in a conventional car today.

Nuclear energy could also provide the power for electrolysis, although producing hydrogen this way would not be significantly cheaper than using renewable sources. In addition, nuclear plants could generate hydrogen without electrolysis: the intense heat of the reactors can split water in a thermochemical reaction. This process might produce hydrogen more cheaply, but its feasibility has not yet been proved. Moreover, any option involving nuclear power has the same drawbacks that have dogged the nuclear electric power industry for decades: the problems of radioactive waste, proliferation and public acceptance.



▲ A major advantage of the Hy-wire prototype fuel-cell car from General Motors is that all the propulsion and control systems are in a skateboardlike chassis, maximizing the interior space.

## A New Energy Infrastructure

BECAUSE THE U.S. has such rich resources of wind, solar and biomass energy, making large amounts of clean, inexpensive hydrogen will not be so difficult. The bigger problem is logistics: how to deliver hydrogen cheaply to many dispersed sites. The U.S. currently has only about 100 small refueling stations for hydrogen, set up for demonstration purposes. In contrast, the country has 170,000 gasoline stations. These stations cannot be easily converted to hydrogen; the gas is stored and handled differently than liquid fuels such as gasoline, requiring alternative technologies at the pump.

The need for a new infrastructure has created a “chicken and egg” problem for the incipient hydrogen economy. Consumers will not buy hydrogen vehicles unless fuel is widely available at a reasonable price, and fuel suppliers will not build hydrogen stations unless there are enough cars to use them. And although the National Research Council's study projects that hydrogen will become competitive with gasoline once a large distribution system is in place, hydrogen might cost much more during the early years of the transition.

One strategy for jump-starting the changeover is to first

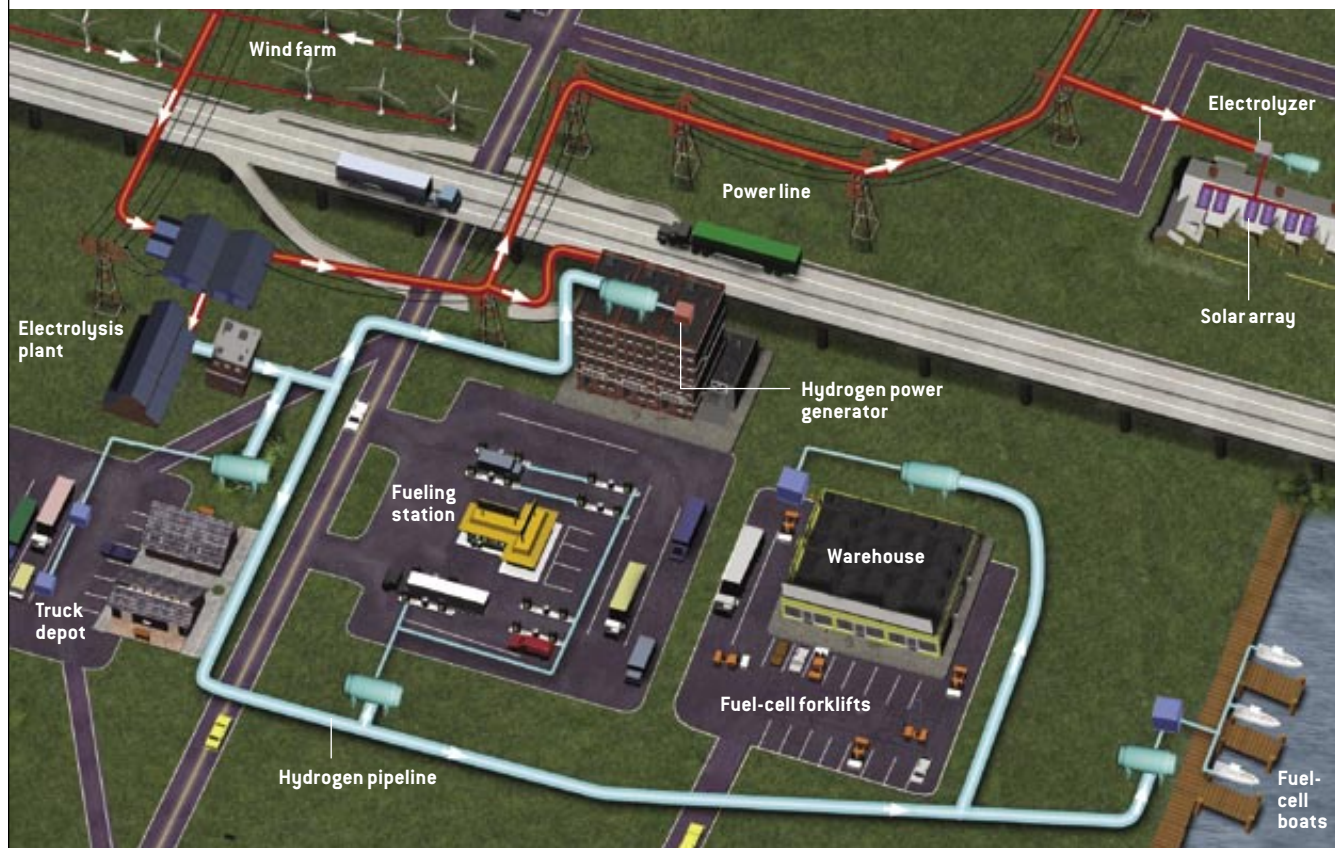
### THE AUTHOR

JOAN OGDEN is professor of environmental science and policy at the University of California, Davis, and co-director of the Hydrogen Pathways Program at the campus's Institute of Transportation Studies. Her primary research interest is technical and economic assessment of new energy technologies, especially in the areas of alternative fuels, fuel cells, renewable energy and energy conservation. She received a Ph.D. in theoretical physics from the University of Maryland in 1977.

## THE MANY USES OF HYDROGEN

Because transporting hydrogen over long distances would be costly, each generation plant would serve the surrounding region. The first users would most likely include fleet vehicles such as trucks and small vehicles that now use electric batteries [for example, forklifts

at a warehouse]. Hydrogen fuel cells could also power marine engines and provide supplemental electricity for office buildings. The owners of fuel-cell cars could stop at hydrogen stations or even generate their own hydrogen at home using the power from solar arrays.



focus on fleet vehicles—local delivery vans, buses and trucks—that do not require an extensive refueling network. Marine engines and locomotives could also run on hydrogen, which would eliminate significant emissions of air pollutants. Hydrogen fuel cells might power small vehicles that now use electric batteries, such as forklifts, scooters and electric bikes. And fuel cells could also be used in stationary power production: for example, they could generate electricity for police stations, military bases and other customers that do not want to rely solely on the power grid. These niche markets could help bring down the cost of fuel cells and encourage energy companies to build the first commercial hydrogen stations.

To make a substantial dent in global oil use and greenhouse gas emissions, however, hydrogen fuel will have to succeed in passenger vehicle markets. Researchers at the University of California, Davis, have concluded that 5 to 10 percent of urban service stations (plus a few stations connecting cities) must offer hydrogen to give fuel-cell car owners roughly the same convenience enjoyed by gasoline customers. GM has estimated that providing national coverage for the first million hydrogen vehicles in the U.S. would require some 12,000

hydrogen stations in cities and along interstates, each costing about \$1 million. Building a full-scale hydrogen system serving 100 million cars in the U.S. might cost several hundred billion dollars, spent over decades. This estimate counts not only the expense of building refueling stations but also the new production and delivery systems that will be needed if hydrogen becomes a popular fuel.

Those numbers may sound daunting, but the World Energy Council projects that the infrastructure costs of maintaining and expanding the North American gasoline economy over the next 30 years will total \$1.3 trillion, more than half of which will be spent in oil-producing countries in the developing world. Most of these costs would go toward oil exploration and production. About \$300 billion would be for oil refineries, pipelines and tankers—facilities that could eventually be replaced by a hydrogen production and delivery system. Building a hydrogen economy is costly, but so is business as usual.

Furthermore, there are several ways to deliver hydrogen to vehicles. Hydrogen can be produced regionally in large plants, then stored as a liquid or compressed gas, and distributed to

refueling stations by truck or gas pipeline. It is also possible to make hydrogen locally at stations—or even in homes—from natural gas or electricity [see box on page 96]. In the early stages of a hydrogen economy, when the number of fuel-cell vehicles is relatively small, truck delivery or on-site production at refueling stations might be the most economical options. But once a large hydrogen demand is established—say, 25 percent of all the cars in a large city—a regional centralized plant with pipeline delivery offers the lowest cost. Centralized hydrogen production also opens the way for carbon sequestration, which makes sense only at large scales.

In many respects, hydrogen is more like electricity than gasoline. Because hydrogen is more costly to store and transport than gasoline, energy companies will most likely produce the fuel all over the country, with each generation plant serving a regional market. What is more, the supply pathways will

The development of the hydrogen fuel infrastructure will be a decades-long process moving in concert with the growing market for fuel-cell vehicles. Through projects such as the California Hydrogen Highways Network and HyWays in Europe, energy companies are already providing hydrogen to test fleets and demonstrating refueling technologies. To enable fuel-cell vehicles to enter mass markets in 10 to 15 years, hydrogen fuel must be widely available at a competitive price by then. Concentrating hydrogen projects in key regions such as southern California or the Northeast corridor might help hasten the growth of the fuel-cell market and reduce the cost of infrastructure investments.

In the near term, the bulk of the hydrogen fuel will most likely be extracted from natural gas. Fueling vehicles this way will cut greenhouse gas emissions only modestly compared with driving gasoline hybrids; to realize hydrogen's full ben-

## Building a hydrogen economy is costly, but so is business as usual.

vary with location. A hydrogen economy in Ohio—which has plentiful coal and many suitable sites for carbon dioxide sequestration—might look entirely different from one in the Pacific Northwest (which has low-cost hydropower) or one in the Midwest (which can rely on wind power and biofuels). A small town or rural area might rely on truck delivery or on-site production, whereas a large, densely populated city might use a pipeline network to transport hydrogen.

Developing a hydrogen economy will certainly entail some financial risks. If an energy company builds giant production or distribution facilities and the fuel-cell market grows more slowly than expected, the company may not be able to recoup its investments. This dilemma is sometimes called the “stranded asset” problem. The energy industry can minimize its risk, though, by adding hydrogen supply in small increments that closely follow demand. For example, companies could build power plants that generate both electricity and a small stream of hydrogen for the early fuel-cell cars. To distribute the hydrogen, the companies could initially use truck delivery and defer big investments such as pipelines until a large, established demand is in place.

### The First Steps

THE ROAD TO a hydrogen transportation system actually consists of several parallel tracks. Raising fuel economy is the essential first step. Developing lightweight cars, more efficient engines and hybrid electric drivetrains can greatly reduce carbon emissions and oil use over the next few decades. Hydrogen and fuel cells will build on this technical progression, taking advantage of the efficiency improvements and the increasing electrification of the vehicles.

efits, energy companies must either make the gas from zero-carbon energy sources or sequester the carbon by-products. Once hydrogen becomes a major fuel—say, in 2025 or beyond—governments should phase in requirements for zero or near-zero emissions in its production. And in the meantime, policymakers should encourage the ongoing efforts to develop clean-power technologies such as wind, solar, biomass gasification and carbon sequestration. The shift to a hydrogen economy can be seen as part of a broader move toward lower-carbon energy.

Although the transition may take several decades, hydrogen fuel-cell vehicles could eventually help protect the global climate and reduce America's reliance on foreign oil. The vast potential of this new industry underscores the importance of researching, developing and demonstrating hydrogen technologies now, so they will be ready when we need them. SA

### MORE TO EXPLORE

**The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.** National Research Council and the National Academy of Engineering. National Academies Press, 2004. Available online at [www.nap.edu/catalog.php?record\\_id=10922#toc](http://www.nap.edu/catalog.php?record_id=10922#toc)

**The Hydrogen Energy Transition: Cutting Carbon from Transportation.** Edited by Daniel Sperling and James S. Cannon. Elsevier, 2004.

**The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate.** Joseph J. Romm. Island Press, 2005.

More information about hydrogen fuel-cell technologies and demonstration programs can be found online at <http://hydrogen.its.ucdavis.edu/>, [www1.eere.energy.gov/hydrogenandfuelcells/](http://www1.eere.energy.gov/hydrogenandfuelcells/), [www.h2mobility.org/index.html](http://www.h2mobility.org/index.html) and [www.iphe.net/NewAtlas/atlas.htm](http://www.iphe.net/NewAtlas/atlas.htm)

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