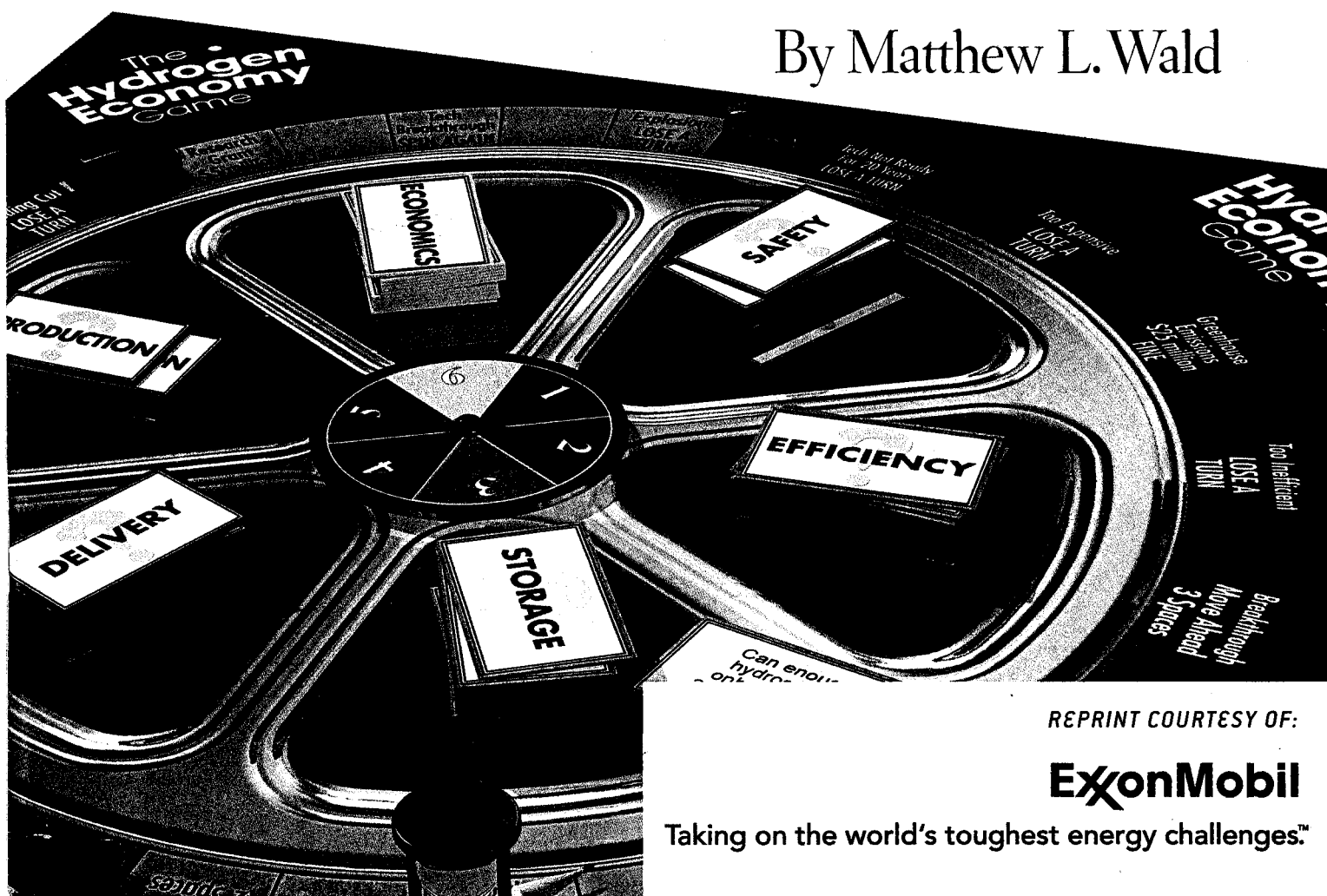


SCIENTIFIC AMERICAN

Questions about a Hydrogen Economy

By Matthew L. Wald

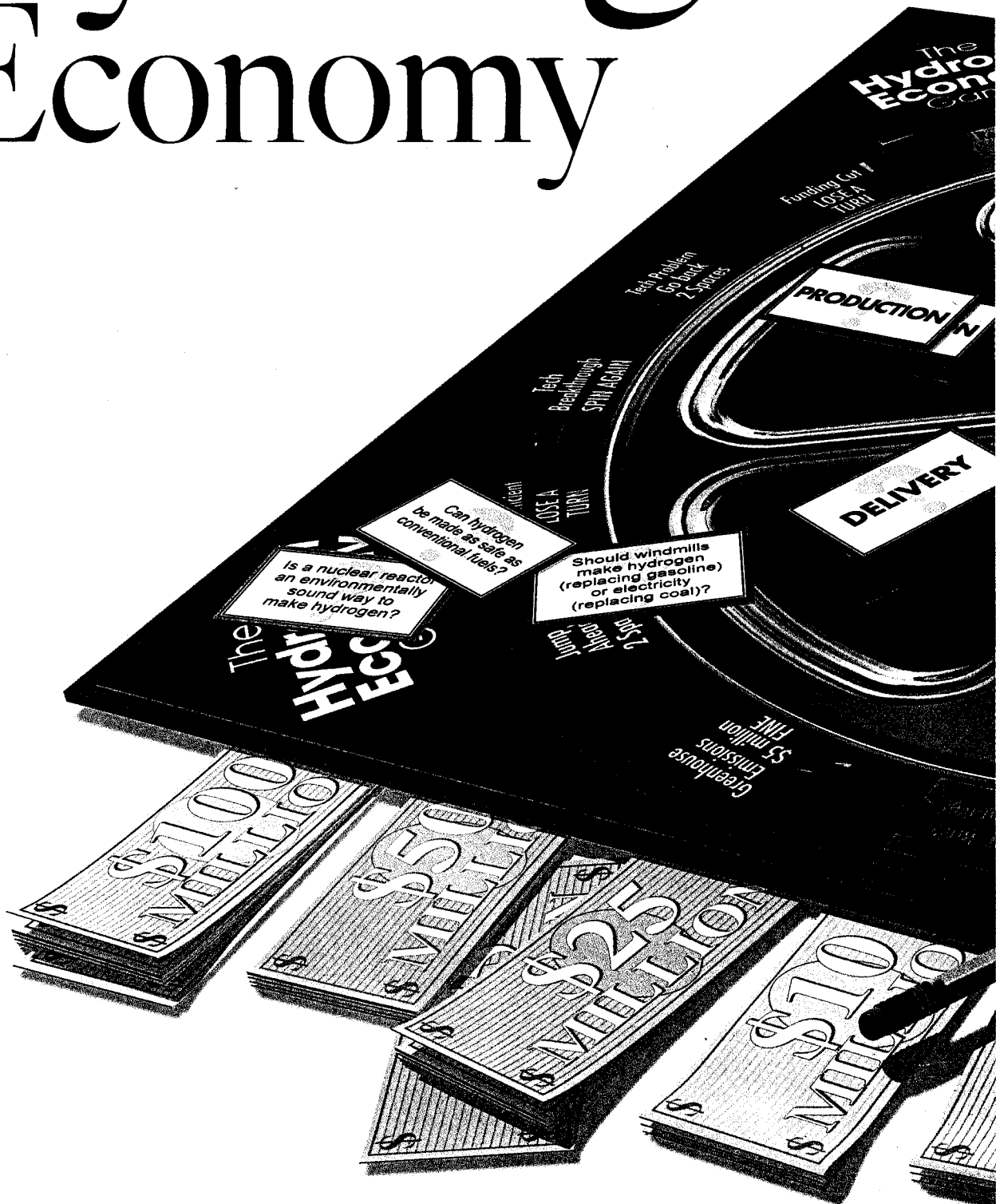


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Questions about a Hydrogen Economy



Much excitement surrounds the progress in fuel cells, but the quest for a hydrogen economy is no trivial pursuit

By Matthew L. Wald



Since mass production of the automobile began, fuel companies and engine manufacturers have continually looked for better ways to power it. And between us, we've achieved some impressive results. Since 1970, for example, we've doubled the fuel economy of the average new car – and reduced emissions by 95%. Over the same period, however, worldwide auto ownership

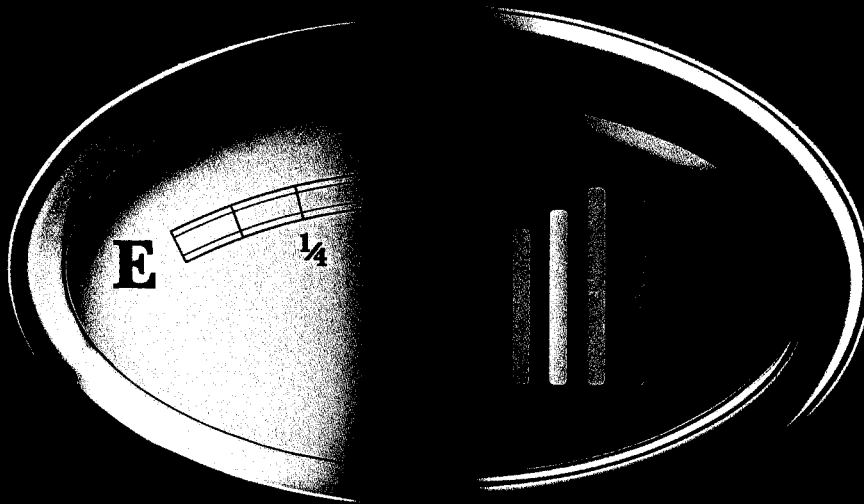
has doubled. So the search goes on.

Like most fuel companies, we're exploring a variety of new ways to power the cars of the future.

But, at ExxonMobil, we're also paying a lot of attention to the here and now. That's why we're still looking at improving the internal combustion engine – and at a new generation of cleaner-burning fuels that could make it work more efficiently. Why? Because even a small improvement to the internal combustion engine now could make a significant difference to emissions sooner than alternatives.

In fact, if we could improve the efficiency of every new car by just 10%, the CO₂ emissions saved worldwide – over just 10 years – would be greater than the annual

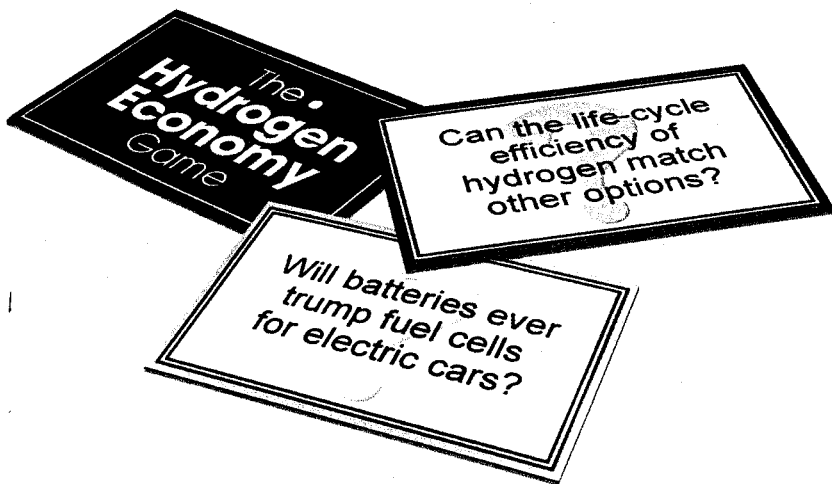
CO₂ emissions of every car in the United States and Canada today. Since we sold our first gallon, we've been at the forefront of fuels technology. As we go forward, the fuels will almost certainly change. But our commitment to improving them won't. exxonmobil.com/energychallenges



**We've been delivering the fuels
of the future for 100 years.**

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Taking on the world's toughest energy challenges.™



In the fall of 2003, a few months after President George W. Bush announced a \$1.7-billion research program to develop a vehicle that would make the air cleaner and the country less dependent on imported oil, Toyota came to Washington, D.C., with two of them. One, a commercially available hybrid sedan, had a conventional, gasoline-fueled internal-combustion engine supplemented by a battery-powered electric motor. It got about 50 miles to the gallon, and its carbon dioxide emissions were just over half those of an average car. The other auto, an experimental SUV, drove its electric motor with hydrogen fuel cells and emitted as waste only water purer than Perrier and some heat. Which was cleaner?

Answering that question correctly could have a big impact on research spending, on what vehicles the government decides to subsidize as it tries to incubate a technology that will wean us away from gasoline and, ultimately, on the environment. But the answer is not what many people would expect, at least according to Robert Wimmer, research manager for technical and regulatory affairs at Toyota. He said that the two vehicles were about the same.

Overview/Hydrogen Economy

- Per a given equivalent unit of fuel, hydrogen fuel cells in vehicles are about twice as efficient as internal-combustion engines. Unlike conventional engines, fuel cells emit only water vapor and heat.
- Hydrogen doesn't exist freely in nature, however, so producing it depends on current energy sources. Sources of hydrogen are either expensive and not widely available [including electrolysis using renewables such as solar, wind or hydropower], or else they produce undesirable greenhouse gases [coal or other fossil fuels].
- Ultimately hydrogen may not be the universal cure-all, although it may be appropriate for certain applications. Transportation may not be one of them.

Wimmer and an increasing number of other experts are looking beyond simple vehicle emissions, to the total effect on the environment caused by the production of the vehicle's fuel and its operation combined. Seen in a broader context, even the supposed great advantages of hydrogen, such as the efficiency and cleanliness of fuel cells, are not as overwhelming as might be thought. From this perspective, coming in neck and neck with a hybrid is something of an achievement; in some cases, the fuel-cell car can be responsible for substantially more carbon dioxide emissions, as well as a variety of other pollutants, the Department of Energy states. And in one way the hybrid is, arguably, superior: it already exists as a commercial product and thus is available to cut pollution now. Fuel-cell cars, in contrast, are expected on about the same schedule as NASA's manned trip to Mars and have about the same level of likelihood.

If that sounds surprising, it is also revealing about the uncertainties and challenges that trail the quest for a hydrogen economy—wherein most energy is devoted to the creation of hydrogen, which is then run through a fuel cell to make electricity. Much hope surrounds the advances in fuel cells and the possibility of a cleaner hydrogen economy, which could include not only transportation but also power for houses and other buildings. Last November U.S. Energy Secretary Spencer Abraham told a Washington gathering of energy ministers from 14 countries and the European Union that hydrogen could “revolutionize the world in which we live.” Noting that the nation's more than 200 million motor vehicles consume about two thirds of the 20 million barrels of oil the U.S. uses every day, President Bush has called hydrogen the “freedom fuel.”

But hydrogen is not free, in either dollars or environmental damage. The hydrogen fuel cell costs nearly 100 times as much per unit of power produced as an internal-combustion engine. To be price competitive, “you've got to be at a nickel a watt, and we're at \$4 a watt,” says Tim R. Dawsey, a research associate at Eastman Chemical Company, which makes polymers for fuel cells. Hydrogen is also about five times as expensive, per unit of usable energy, as gasoline. Simple dollars are only one speed bump on the road to the hydrogen economy. Another is that



FACE OFF: If total life-cycle environmental impact of a given fuel is included, the Toyota Prius (right), a hybrid that has a gasoline internal-combustion



engine supplemented by an electric motor, compares favorably with the company's experimental hydrogen fuel-cell SUV (left).

supplying the energy required to make pure hydrogen may itself cause pollution. Even if that energy is from a renewable source, like the sun or the wind, it may have more environmentally sound uses than the production of hydrogen. Distribution and storage of hydrogen—the least dense gas in the universe—are other technological and infrastructure difficulties. So is the safe handling of the gas. Any practical proposal for a hydrogen economy will have to address all these issues.

Which Sources Make Sense?

HYDROGEN FUEL CELLS have two obvious attractions. First, they produce no pollution at point of use [see “Vehicle of Change,” by Lawrence D. Burns, J. Byron McCormick and Christopher E. Borroni-Bird; *SCIENTIFIC AMERICAN*, October 2002]. Second, hydrogen can come from myriad sources. In fact, the gas is not a fuel in the conventional sense. A fuel is something found in nature, like coal, or refined from a natural product, like diesel fuel from oil, and then burned to do work. Pure hydrogen does not exist naturally on earth and is so highly processed that it is really more of a carrier or medium for storing and transporting energy from some original source to a machine that makes electricity. “The beauty of hydrogen is the fuel diversity that’s possible,” said David K. Garman, U.S. assistant secretary for energy efficiency and renewable energy. Each source, however, has an ugly side.

For instance, a process called electrolysis makes hydrogen by splitting a water molecule with electricity [see illustration on page 9]. The electricity could come from solar cells, windmills, hydropower or safer, next-generation nuclear reactors [see “Next-Generation Nuclear Power,” by James A. Lake, Ralph G. Bennett and John F. Kotek; *SCIENTIFIC AMERICAN*, January 2002]. Researchers are also trying to use microbes to transform biomass, including parts of crops that now have no economic value, into hydrogen. In February researchers at the University of Minnesota and the University of Patras in Greece announced a chemical reactor that generates hydrogen from ethanol mixed with water. Though appealing, all these technologies are either unaffordable or unavailable on a commercial scale and are likely to remain so for many years to come, according to experts.

Hydrogen could be derived from coal-fired electricity, which is the cheapest source of energy in most parts of the country. Critics argue, though, that if coal is the first ingredient for the hydrogen economy, global warming could be exacerbated through greater release of carbon dioxide.

Or hydrogen could come from the methane in natural gas, methanol or other hydrocarbon fuel [see illustration on page 9]. Natural gas can be reacted with steam to make hydrogen and carbon dioxide. Filling fuel cells, however, would preclude the use of natural gas for its best industrial purpose today: burning in high-efficiency combined-cycle turbines to generate electricity. That, in turn, might again lead to more coal use. Combined-cycle plants can turn 60 percent of the heat of burning natural gas into electricity; a coal plant converts only about 33 percent. Also, when burned, natural gas produces just over half as much carbon dioxide per unit of heat as coal does, 117 pounds per million Btu versus 212. As a result, a kilowatt-hour of electricity made from a new natural gas plant has slightly over one fourth as much carbon dioxide as a kilowatt-hour from coal. (Gasoline comes between coal and natural gas, at 157 pounds of carbon dioxide per million Btu.) In sum, it seems better for the environment to use natural gas to make electricity for the grid and save coal, rather than turning it into hydrogen to save gasoline.

Two other fuels could be steam-reformed to give off hydrogen: the oil shipped from Venezuela or the Persian Gulf and, again, the coal from Appalachian mines. To make hydrogen from fossil fuels in a way that does not add to the release of climate-changing carbon dioxide, the carbon must be captured so that it does not enter the atmosphere. Presumably this process would be easier than sequestering carbon from millions of

THE AUTHOR

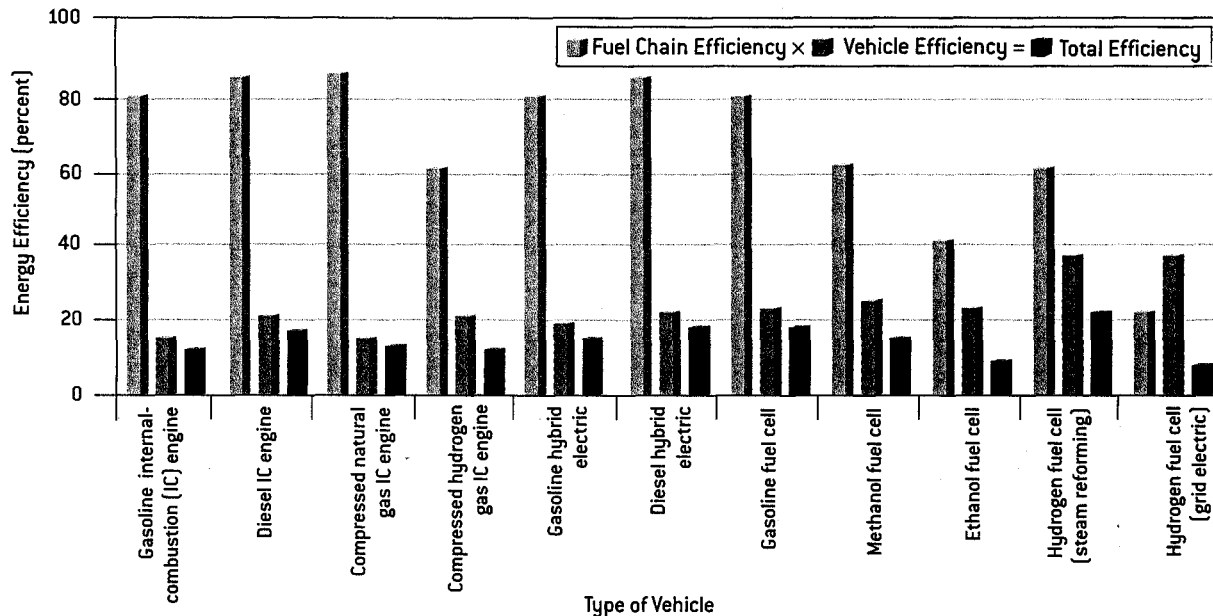
MATTHEW L. WALD is a reporter at the *New York Times*, where he has been covering energy since 1979. He has written about oil refining; coal mining; electricity production from coal, natural gas, uranium, wind and solar energy; electric and hybrid automobiles; and air pollution from energy use. His current assignment is in Washington, D.C., where he also writes about transportation safety and other technical topics.

TOYOTA

WELL-TO-WHEELS ENERGY EFFICIENCY

Total energy efficiency includes not only vehicle operation but also the energy required to produce fuel. Extracting oil, refining gasoline

and trucking that fuel to filling stations for internal-combustion engines is more efficient than creating hydrogen for fuel cells.



tailpipes. Otherwise, the fuels might as well be burned directly.

"If you look at it from the whole system, not the individual sector, you may do better to get rid of your coal-fired power plants, because coal is such a carbon-intensive fuel," says Michael Wang, an energy researcher at Argonne National Laboratory. Coal accounts for a little more than half the kilowatt-hours produced in the U.S.; about 20 percent is from natural gas. The rest comes from mostly carbon-free sources, primarily nuclear reactors and hydroelectricity. Thus, an effort to replace the coal-fired electric plants would most likely take decades.

In any case, if hydrogen were to increase suddenly in supply, fuel cells might not even be the best use for the gas. In a recent paper, Reuel Shinnar, professor of chemical engineering at the City College of New York, reviewed the alternatives for power and fuel production. Rather than the use of hydrogen as fuel, he suggested something far simpler: increased use of hydrocracking and hydrotreating. The U.S. could save three million barrels of oil a day that way, Shinnar calculated. Hydrocracking and hydrotreating both start with molecules in crude oil that are unsuitable for gasoline because they are too big and have a carbon-to-hydrogen ratio that is too heavy with carbon. The processes are expensive but still profitable, because they allow the refineries to take ingredients that are good for only low-value products, such as asphalt and boiler fuel, and turn them into gasoline. It is like turning chuck steak into sirloin.

What about Conversion Costs?

IF HYDROGEN PRODUCTION is dirty and expensive, could its impressive energy efficiency at point of use make up for those downsides? Again, the answer is complicated.

A kilo of hydrogen contains about the same energy as a gal-

lon of unleaded regular gas—that is, if burned, each would give off about the same amount of heat. But the internal-combustion engine and the fuel cell differ in their ability to extract usable work from that fuel energy. In the engine, most of the energy flows out of the tailpipe as heat, and additional energy is lost to friction inside the engine. In round numbers, advocates and detractors agree, a fuel cell gets twice as much work out of a kilo of hydrogen as an engine gets out of a gallon of gas. (In a stationary application—such as a basement appliance that takes the hydrogen from natural gas and turns it into electricity to run the household—efficiency could be higher, because the heat given off by the fuel-cell process could also be used—for example, to heat tap water.)

There is, in fact, a systematic way to evaluate where best to use each fuel. A new genre of energy analysis, "well to wheels," compares the energy efficiency of every known method to turn a vehicle's wheels [see illustration above]. The building block of the well-to-wheels performance is "conversion efficiency." At every step of the energy chain, from pumping oil out of the ground to refining it to burning it in an engine, some of the original energy potential of the fuel is lost.

The first part of the well-to-wheels determination is what engineers call "well to tank": what it takes to make and deliver a fuel. When natural gas is cracked for hydrogen, about 40 percent of the original energy potential is lost in the transfer, according to the DOE Office of Energy Efficiency and Renewable Energy. Using electricity from the grid to make hydrogen by electrolysis of water causes a loss of 78 percent. (Despite the lower efficiency of electrolysis, it is likely to predominate in the early stages of a hydrogen economy because it is convenient—producing the hydrogen where it is needed and thus avoiding ship-

ping problems.) In contrast, pumping a gallon of oil out of the ground, taking it to a refinery, turning it into gasoline and getting that petrol to a filling station loses about 21 percent of the energy potential. Producing natural gas and compressing it in a tank loses only about 15 percent.

The second part of the total energy analysis is “tank to wheels,” or the fraction of the energy value in the vehicle’s tank that actually ends up driving the wheels. For the conventional gasoline internal-combustion engine, 85 percent of the energy in the gasoline tank is lost; thus, the whole system, well to tank combined with tank to wheels, accounts for a total loss of 88 percent.

The fuel cell converts about 37 percent of the hydrogen’s energy value to power for the wheels. The total loss, well to wheels, is about 78 percent if the hydrogen comes from steam-reformed natural gas. If the source of the hydrogen is electrolysis from coal, the loss from the well (a mine, actually) to tank is 78 percent; after that hydrogen runs through a fuel cell, it loses another 43 percent, with the total loss reaching 92 percent.

Wally Rippel, a research engineer at AeroVironment in Monrovia, Calif., who helped to develop the General Motors EV-1 electric car and the NASA Helios Solar Electric airplane, offers another way to look at the situation. He calculates that in a car that employs an electric motor to turn the wheels, a kilowatt-hour used to recharge batteries will propel the auto

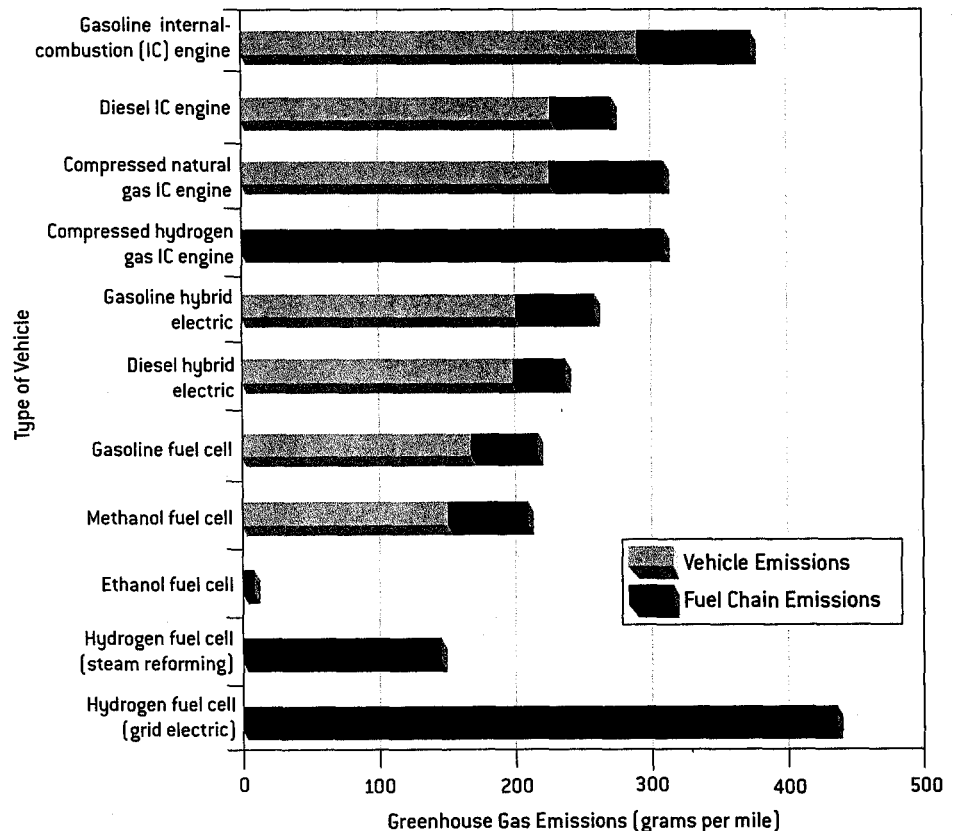
three times as far as if that same kilowatt-hour were instead used to make hydrogen for a fuel cell.

All these facts add up to an argument *not* to use electricity to make hydrogen and then go back to electricity again with an under-the-hood fuel cell. But there is one strong reason to go through inefficient multiple conversions. They may still make economic sense, and money is what has shaped the energy markets so far. That is, even if the hydrogen system is very wasteful of energy, there are such huge differences in the cost of energy from various sources that it might make sense to switch to a system that lets us go where the cheapest energy is.

Walter “Chip” Schroeder, president and chief executive of Proton Energy Systems, a Connecticut company that builds electrolysis machines, explains the economic logic. Coal at current prices (which is to say, coal at prices that are likely to prevail for years to come) costs a little more than 80 cents per million Btu. Gasoline at \$1.75 a gallon (which seems pricey at the moment but in a few months or years could look cheap) is about \$15.40. The mechanism for turning a Btu from coal into a Btu that will run a car is cumbersome, but in the transition, “you end up with wine, not water,” he says. Likewise, he describes his device to turn water into hydrogen as an “arbitrage machine.” “Arbitrage” is the term used by investment bankers or stock or commodities traders to describe buying low and selling high, but it usually refers to small differences in the price

TOTAL EMISSIONS OF VEHICLES

Emissions of greenhouse gases [carbon dioxide or equivalent] vary depending on the combined effects of the vehicle’s operation and the source of the fuel. Fuel-cell vehicles emit no greenhouse gases themselves, but the creation of the hydrogen fuel can be responsible for more emissions overall than conventional gasoline internal-combustion engines are. [The Energy Department calculates that ethanol derived from corn has almost no greenhouse gas emissions, because carbon emitted by ethanol use is reabsorbed by new corn.]



LUCY READING, SOURCE: DEPARTMENT OF ENERGY

of a stock or the value of a currency between one market or another. "You can't make reasonable policy without understanding just how extreme the value differentials in our energy marketplace are," Schroeder says.

How to Deliver the Hydrogen?

DIFFERENT SOURCES of energy may not be as fungible as money is in arbitrage, however. There is a problem making hydrogen conveniently available at a good cost, at least if the hydrogen is going to come from renewable sources such as solar, hydropower or wind that are practical in only certain areas of the country.

Hydrogen from wind, for example, is competitive with gasoline when wind power costs three cents a kilowatt-hour, says Garman of the DOE. That occurs where winds blow steadily. "Where I might get three-cent wind tends to be in places where people don't live," he notes. In the U.S., such winds exist in a belt running from Montana and the Dakotas to Texas. The electric power they produce would have a long way to go to reach the end users—with energy losses throughout the grid along the way. "You can't get the electrons out of the Dakotas because of transmission constraints," Garman points out. "Maybe a hydrogen pipeline could get the tremendous wind resource carried to Chicago," the nearest motor-fuel market.

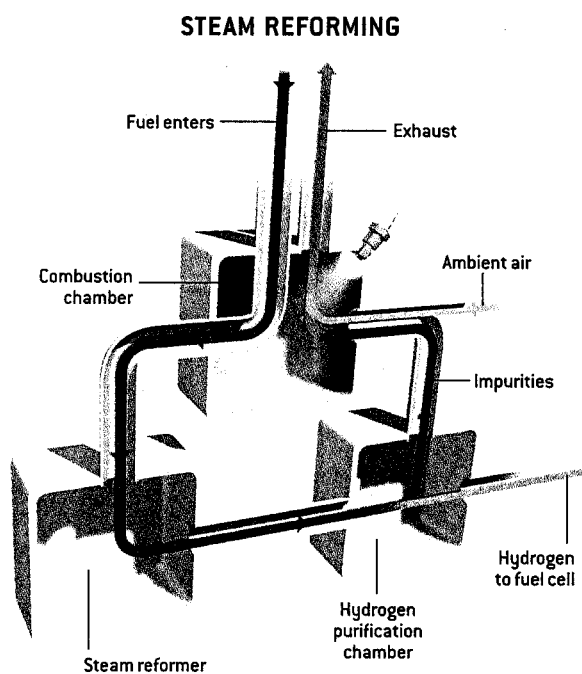
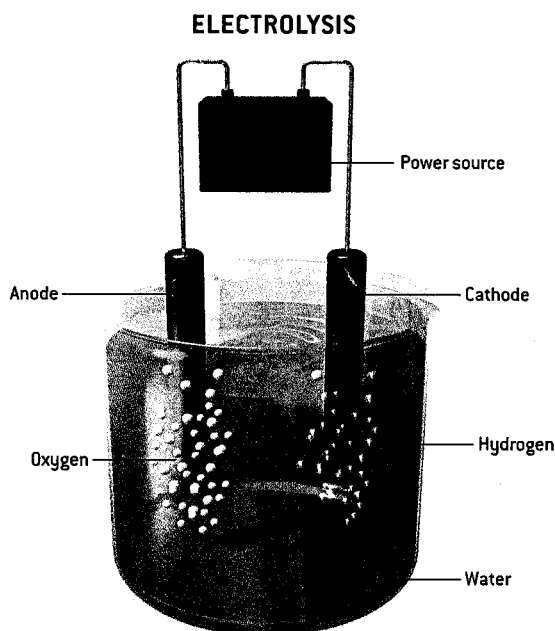
That is, if such a pipeline were even practical to build. Given hydrogen's low density, it is far harder to deliver than, for instance, natural gas. To move large volumes of any gas requires compressing it, or else the pipeline has to have a diameter similar to that of an airplane fuselage. Compression takes work, and that drains still more energy from the total production process. Even in this instance, managing hydrogen is trickier than dealing with other fuel gases. Hydrogen compressed to about 790 atmospheres has less than a third of the energy of the methane in natural gas at the same pressure, points out a recent study by three European researchers, Ulf Bossel, Baldur Eliasson and Gordon Taylor.

A related problem is that a truck that could deliver 2,400 kilos of natural gas to a user would yield only 288 kilos of hydrogen pressurized to the same level, Bossel and his colleagues find. Put another way, it would take about 15 trucks to deliver the hydrogen needed to power the same number of cars that could be served by a single gasoline tanker. Switch to liquid hydrogen, and it would take only about three trucks to equal the one gasoline tanker, but hydrogen requires substantially more effort to liquefy. Shipping the hydrogen as methanol that could be reformed onboard the vehicle [see illustration below] would ease transport, but again, the added transition has an energy penalty. These facts argue for using the hydrogen where it is pro-

CREATING HYDROGEN

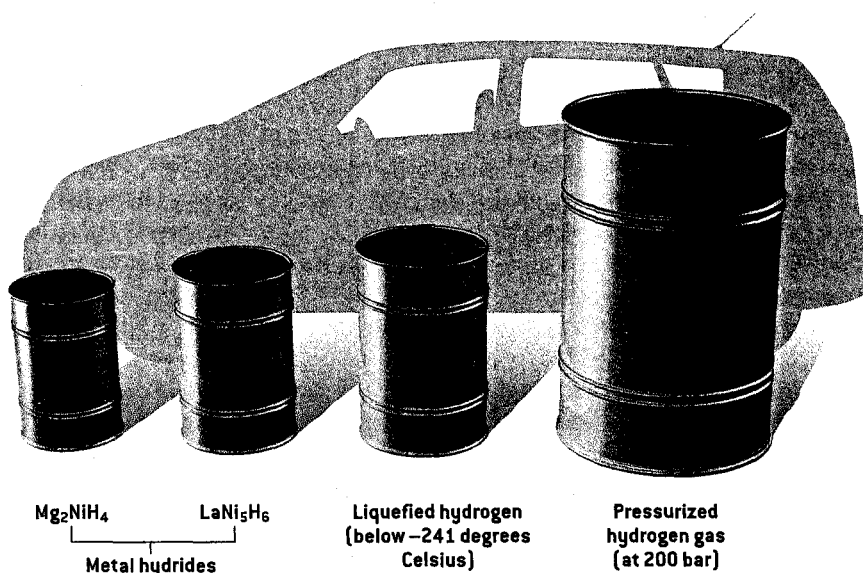
Two main methods are known for extracting hydrogen, which does not occur in pure form naturally on the earth. Electrolysis (left) uses electric current to split molecules of water (H_2O). A cathode (negative terminal) attracts hydrogen atoms, and an anode (positive) attracts oxygen; the two gases bubble up into

air and can be captured. In steam reforming (right), a hydrocarbon such as methanol (CH_3OH) first vaporizes in a heated combustion chamber. A catalyst in the steam reformer breaks apart fuel and water vapor to produce components including hydrogen, which is then separated and routed to a fuel cell.



SAME HYDROGEN, DIFFERENT VOLUMES

Containing the lightest gas in the universe onboard a car presents a challenge, as is clear from the differences in volume of some options for storing four kilograms of hydrogen—enough for a 250-mile driving range. [Four kilograms of hydrogen holds about the same energy as four gallons of gasoline. Because fuel cells are about twice as efficient as internal-combustion engines, that four kilograms takes the car as far as eight gallons of gasoline.] Current alternatives, including tanks that hold pressurized gas or liquefied hydrogen, are too big. Experimental metal hydrides or other solid-state technologies might be able to release hydrogen on demand and be recharged later, but they also carry a weight penalty or an energy penalty for the chemical transformations.



duced, which may be distant from the major motor-fuel markets.

No matter how hydrogen reaches its destination, the difficulties of handling the elusive gas will not be over. Among hydrogen's disadvantages is that it burns readily. All gaseous fuels have a minimum and maximum concentration at which they will burn. Hydrogen's range is unusually broad, from 2 to 75 percent. Natural gas, in contrast, burns between 5 and 15 percent. Thus, as dangerous as a leak of natural gas is, a hydrogen leak is worse, because hydrogen will ignite at a wider range of concentrations. The minimum energy necessary to ignite hydrogen is also far smaller than that for natural gas.

And when hydrogen burns, it does so invisibly. NASA published a safety manual that recommends checking for hydrogen fires by holding a broom at arm's length and seeing if the straw ignites. "It's scary—you cannot see the flame," says Michael D. Amiridis, chair of the department of chemical engineering at the University of South Carolina, which performs fuel-cell research under contract for a variety of companies. A successful fuel-cell car, he says, would have "safety standards at least equivalent to the one I have now." A major part of the early work on developing a hydrogen fueling supply chain has been building warning instruments that can reliably detect hydrogen gas.

A Hole for Hydrogen

DESPITE THE TECHNOLOGICAL and infrastructure obstacles, a hydrogen economy may be coming. If it is, it will most likely resemble the perfume economy, a market where quantities are so small that unit prices do not matter. Chances are good that it will start in cellular phones and laptop computers, where consumers might not mind paying \$10 a kilowatt-hour for electricity from fuel cells; a recent study by the fuel-cell industry predicts that the devices could be sold in laptop computers this year. It might eventually move to houses, which will run nicely on five

kilowatts or so and where an improvement in carbon efficiency is highly desirable because significant electricity demand exists almost every hour of the day. But hydrogen cells may not appear in great numbers in driveways, where cars have a total energy requirement of about 50 kilowatts apiece but may run only an average of two hours a day—a situation that is exactly backward from where a good engineer would put a device like a fuel cell, which has a low operating cost but a high cost per unit of capacity. Although most people may have heard of fuel cells as alternative power sources for cars, cars may be the last place they'll end up on a commercial scale.

If we need to find substitutes for oil for transportation, we may look to several places before hydrogen. One is natural gas, with very few technical details to work out and significant supplies available. Another is electricity for electric cars. Battery technology has hit some very significant hurdles, but they might be easier to solve than those of fuel cells. If we have to, we can run vehicles on methanol from coal; the Germans did it in the 1940s, and surely we could figure it out today.

Last, if we as a society truly support the development of renewable sources such as windmills and solar cells, they could replace much of the fossil fuels used today in the electric grid system. With that development, plus judicious conservation, we would have a lot of energy left over for the transportation sector, the part of the economy that is using up the oil and making us worry about hydrogen in the first place. ■

MORE TO EXPLORE

The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academies Press, 2004.

The Hype about Hydrogen. Joseph J. Romm. Island Press, 2004.

U.S. Department of Energy, Energy Efficiency and Renewable Energy Web pages on hydrogen: www.eere.energy.gov/hydrogenandfuelcells/

Hydrogen: promise and challenge

Hydrogen is the most abundant element in the universe. When burned, it produces no emissions but water. Combined with oxygen, hydrogen can power fuel cells, an advanced technology under development for automobiles. Could hydrogen be the key to our energy future?

To become a reality, hydrogen fuel faces three major challenges:

First, how do we produce the hydrogen? Although common in many compounds, such as water, pure hydrogen is rare. Like electricity, it's a clean energy carrier, but must be made from another energy source. One possibility is to produce hydrogen from hydrocarbon fuels, such as natural gas.

An alternative process called electrolysis can extract hydrogen from water, but only by using lots of electricity, which is typically generated by fossil or nuclear fuels.

Therefore, and unfortunately, all known ways of producing hydrogen today use energy and are costly, making it much more expensive than gasoline.

Second, where do we produce the hydrogen? We could make hydrogen in large central facilities and then move it to consumers. If so, we would need a new infrastructure of high pressure pipelines, storage facilities and retail station pumps. Or it may be possible to produce and store hydrogen in a smaller installation at a modified retail station.

Another option could be to make hydrogen on the vehicle itself. We are developing technology to produce *hydrogen from gasoline* on

board a fuel cell automobile as it is needed, thereby using the existing gasoline infrastructure.

Whichever option is chosen, we will need to address very real safety concerns with the distribution and use of high-pressure hydrogen, whose combustion properties merit very careful consideration.

Third, can hydrogen meet our economic and environmental goals better than other options? Even today, showrooms feature

new conventional engines and some electric-gasoline hybrids that also hold the promise of cleaner, more efficient automobiles.

There's only one way to find out which technologies are the best — let them compete for your business in the marketplace. Consumers want to know not only which vehicle and fuel combination are the cleanest and most efficient, but which provide the highest safety, reliability and performance at the lowest cost.

Hydrogen deserves a chance to earn its place and could become important in several decades if the formidable challenges it poses can be resolved. ExxonMobil is working with automobile companies to develop a range of advanced vehicle and fuel technologies. We are participating in discussions with governments, public interest groups and other firms around the world to evaluate all options, including hydrogen.

Our objective remains the same — offering you, the consumer, the best, cleanest and most affordable fuel for your transportation needs.

Hydrogen and our energy future

ExxonMobil™

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