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The Truth About Hydrogen

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WHEN ASSESSING THE State of the Union in 2003, President Bush declared it was time to take a crucial step toward protecting our environment. He announced a $1.2 billion initiative to begin developing a national hydrogen infrastructure: a coast-to-coast network of facilities that would produce and distribute the hydrogen for powering hundreds of millions of fuel cell vehicles. Backed by a national commitment, he said, "our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free." With two years to go on the first, $720 million phase of the plan, PM asks that perennial question of every automotive journey: Are we almost there?

And the inevitable answer from the front seat: No. Promises of a thriving hydrogen economy — one that supports not only cars and trucks, but cellphones, computers, homes and whole neighborhoods — date back long before this presidency, and the road to fulfilling them stretches far beyond its horizon.

The Department of Energy projects the nation's consumption of fossil fuels will continue to rise — increasing 34 percent by 2030. When burned, these carbon-based fuels release millions of tons of carbon dioxide into the atmosphere, where the gas traps heat and is believed to contribute to global warming.

At first glance, hydrogen would seem an ideal substitute for these problematic fuels. Pound for pound, hydrogen contains almost three times as much energy as natural gas, and when consumed its only emission is pure, plain water. But unlike oil and gas, hydrogen is not a fuel. It is a way of storing or transporting energy. You have to make it before you can use it — generally by extracting hydrogen from fossil fuels, or by using electricity to split it from water.

And while oil and gas are easy to transport in pipelines and fuel tanks — they pack a lot of energy into a dense, stable form — hydrogen presents a host of technical and economic challenges. The lightest gas in the universe isn't easy to corral. Skeptics say that hydrogen promises to be a needlessly expensive solution for applications for which simpler, cheaper and cleaner alternatives already exist. "You have to step back and ask, 'What is the point?'" says Joseph Romm, executive director of the Center for Energy & Climate Solutions.

Though advocates promote hydrogen as a panacea for energy needs ranging from consumer electronics to home power, its real impact will likely occur on the nation's highways. After all, transportation represents two-thirds of U.S. oil consumption. "We're working on biofuels, ethanol, biodiesel and other technologies," says David Garmin, assistant secretary of energy, "but it's only hydrogen, ultimately, over the long term, that can delink light-duty transportation from petroleum entirely."

The Big Three U.S. automakers, as well as Toyota, Honda, BMW and Nissan, have all been preparing for that day. Fuel cell vehicles can now travel 300 miles on 17.6 pounds of hydrogen and achieve speeds of up to 132 mph. But without critical infrastructure, there will be no hydrogen economy. And the practical employment of hydrogen power involves major hurdles at every step — production, storage, distribution and use. Here's how those challenges stack up.

HURDLE 1: Production

The United States already uses some 10 million tons of hydrogen each year for industrial purposes, such as making fertilizer and refining petroleum. If hydrogen-powered vehicles are to become the norm, we'll need at least 10 times more. The challenge will be to produce it in an efficient and environmentally friendly way.

FOSSIL FUELS: At present, 95 percent of America's hydrogen is produced from natural gas. Through a process called steam methane reformation, high temperature and pressure break the hydrocarbon into hydrogen and carbon oxides — including carbon dioxide, which is released into the atmosphere as a greenhouse gas. Over the next 10 or 20 years, fossil fuels most likely will continue to be the main feedstock for the hydrogen economy. And there's the rub: Using dirty energy to make clean energy doesn't solve the pollution problem-it just moves it around. "As a CO2 reducer, hydrogen stinks," Romm says.

Capturing that carbon dioxide and trapping it underground would make the process more environmentally friendly. In July, General Electric and BP Amoco PLC announced plans to develop as many as 15 power plants over the next 10 years that will strip hydrogen from natural gas to generate electricity; the waste carbon dioxide will be pumped into depleted oil and gas fields. And the Department of Energy is largely funding a 10-year, $950 million project to build a coal-fed plant that will produce hydrogen to make electricity, and likewise lock away carbon dioxide to achieve what it bills as "the world's first zero-emissions fossil fuel plant."

Whether carbon dioxide will remain underground in large-scale operations remains to be seen. In addition, natural gas is a limited resource; the cost of hydrogen would be subject to its price fluctuations.

ELECTROLYSIS: Most of the remainder of today's hydrogen is made by electrically splitting water into its constituent parts, hydrogen and oxygen. This year, a PM Breakthrough Award went to GE's Richard Bourgeois for designing an electrolyzer that could drastically reduce the cost of that process. But because fossil fuels generate more than 70 percent of the nation's electrical power, hydrogen produced from the grid would still be a significant source of greenhouse gas. If solar, wind or other renewable resources generate the electricity, hydrogen could be produced without any carbon emissions at all.

NUCLEAR POWER: Next-generation nuclear power plants will reach temperatures high enough to produce hydrogen as well as electricity, either by adding steam and heat to the electrolysis process, or by adding heat to a series of chemical reactions that split the hydrogen from water. Though promising in the lab, this technology won't be proved until the first Generation IV plants come on line — around 2020.

PURE ENERGY: *An employee at the Ballard plant in Vancouver,* *British Columbia, seals the critical component of fuel cells, which convert hydrogen into electric power.*

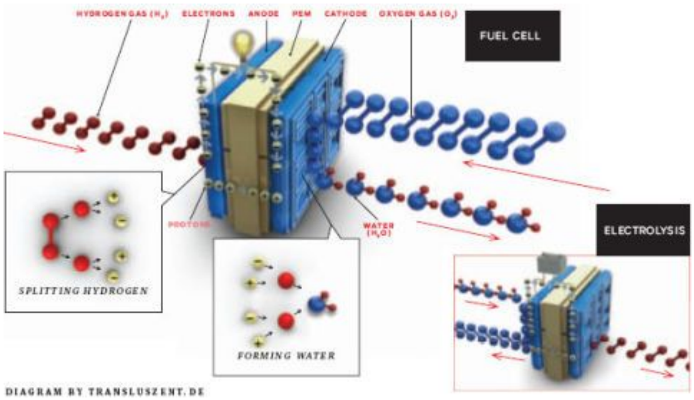

DIAGRAM BY TRANSLUSZENT.DE

HYDROGEN IS THE universe's simplest atom: a single electron orbiting a single proton. In a fuel cell, incoming hydrogen gas is separated by a catalyst at the anode into protons and electrons. The protons pass directly through a proton exchange membrane (PEM), while electrons are forced through an external circuit, causing electric current to flow. When the protons and electrons meet at the cathode, they join with oxygen to form water and heat, which are released as exhaust.

A single fuel cell produces just over 1 volt, so hundreds are stacked together for typical applications. PEM fuel cells, used in NASA's Gemini flights in the 1960s, are the design of choice for fuel cell cars, but other configurations are suited for applications ranging from laptops to power plants.

Electrolysis is the exact opposite process. Electricity from a power supply splits incoming water into protons, electrons and oxygen, which is released as a gas. Electrons reunite with protons at the cathode to produce hydrogen gas.

Other electrolysis designs being developed use solid-oxide membranes instead of PEMs, which improve efficiency but require operating temperatures of 900 to 1500 F — heat that could be supplied by nuclear reactors.

HURDLE 2: Storage

At room temperature and pressure, hydrogen's density is so low that it contains less than one-three-hundredth the energy in an equivalent volume of gasoline. In order to fit into a reasonably sized storage tank, hydrogen has to be somehow squeezed into a denser form.

LIQUEFACTION: Chilled to near absolute zero, hydrogen gas turns into a liquid containing one-quarter the energy in an equivalent volume of gasoline. The technology is well-proven: For decades, NASA has used liquid hydrogen to power vehicles such as the space shuttle. The cooling process requires a lot of energy, though-roughly a third of the amount held in the hydrogen. Storage tanks are bulky, heavy and expensive.

COMPRESSION: Some hydrogen-powered vehicles use tanks of room-temperature hydrogen compressed to an astounding 10,000 psi. The Sequel, which GM unveiled in January 2005, carries 8 kilograms of compressed hydrogen this way-enough to power the vehicle for 300 miles. Refueling with compressed hydrogen is relatively fast and simple. But even compressed, hydrogen requires large- volume tanks. They take up four to five times as much space as a gas tank with an equivalent mileage range. Then again, fuel cell cars can accommodate bigger tanks because they contain fewer mechanical parts.

SOLID-STATE: Certain compounds can trap hydrogen molecules at room temperature and pressure, then release them upon demand. So far, the most promising research has been conducted with a class of materials called metal hydrides. These materials are stable, but heavy: A 700-pound tank might hold a few hours' fuel. However, exotic compounds now being studied could provide a breakthrough to make hydrogen storage truly practical. "High-pressure tanks are a stopgap until we can develop materials that will allow us to do solid-state storage efficiently," says Dan O'Connell, a director of GM's hydrogen vehicle program.

HURDLE 3: Distribution

Even in portable form, hydrogen is a tough substance to move from place to place. It can embrittle steel and other metals, weakening them to the point of fracture.

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CLEAN FUEL: This fueling station in Burlington, Vt., uses electricity to convert water into hydrogen for powering fuel cell cars. It is part of a Department of Energy program for testing alternative fuels in colder climates.**TRUCKING AND RAIL:** Currently, most hydrogen is transported either in liquid form by tankers or as compressed gas in cylinders by trailers. Both methods are inefficient. Trucking compressed hydrogen 150 miles, for instance, burns diesel equivalent to 11 percent of the energy the hydrogen stores. It also requires a lot of round trips: A 44-ton vehicle that can carry enough gasoline to refuel 800 cars could only carry enough hydrogen to fuel 80 vehicles.

PIPELINES: One way to avoid this endless back-and-forth would be to send the hydrogen through a pipeline. About 700 miles of hydrogen pipelines now operate in the States, generally near large users such as oil refineries. The longest in the world is a 250-mile line between Belgium and France. Treating pipelines to protect them from embrittlement and high pressure makes them expensive up front-about $1 million per mile. But once built, they are the cheapest way to deliver high volumes of hydrogen.

LOCAL PRODUCTION: Given the difficulty of transporting hydrogen, why not just make it where you need it? That's what's done at roughly half the 36 hydrogen fueling stations currently operating in the U.S. Four rely on natural gas; the rest use electrolysis. In 2003, Honda introduced a Home Energy Station that performs steam reformation right in the owner's garage-but because natural gas is the feedstock, it still releases carbon dioxide to the atmosphere.

A greenhouse gas-free approach would use on-site wind or solar power to produce hydrogen through electrolysis. Honda also designed a solar-powered hydrogen refueling station, which has been operating at the company's California lab since 2001. If the national power supply becomes more eco-friendly, clean electrolysis could run off the grid.

ON-BOARD PRODUCTION: Several prototype vehicles make their own hydrogen from stored hydrocarbons, eliminating the question of distribution altogether. The DaimlerChrysler NECAR 3, for example, produces hydrogen from methanol. Researchers are also experimenting with more futuristic on-board production technologies, which combine ordinary water with reagents like boron or aluminum to produce hydrogen, oxygen and a metal oxide residue. These, however, are still a long way off.

HURDLE 4: Use

Once hydrogen reaches consumers, is there anything they can do with it except drive vehicles? Home energy generation is one other option. The question is whether hydrogen would be more practical than current methods. Hydrogen produced by steam reformation or by electrolysis loses energy when it is converted into electricity. The resulting efficiency is roughly equal to that of today's power plants — which pay a lot less for raw materials. Direct generation of electricity through wind and solar power will also be more efficient for most stationary applications. That leaves transportation as the most promising use for hydrogen.

INTERNAL COMBUSTION: The most straight-forward approach is to burn hydrogen in an adapted model of your garden-variety internal-combustion engine (ICE). Since little modification is required, these engines are relatively cheap, and 25 percent more efficient than gasoline-powered engines. BMW built its first hydrogen ICE back in the 1970s, and the concept still has legs: Ford began production of a hydrogen ICE shuttle bus last July.

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GREEN BEER: The four 250-kilowatt hydrogen fuel cells at the Sierra Nevada Brewery in Chico, Calif., run on a combination of natural gas and methane. They generate enough electricity to power the entire production plant.**FUEL CELL:** First invented in 1839, a fuel cell combines hydrogen and oxygen to generate electricity without any moving parts. Several different varieties exist, but only the proton exchange membrane (PEM) fuel cell is lightweight and responsive enough to be practical for vehicle use. Though twice as efficient as ICEs, PEM fuel cells are hindered by high prices — even in mass production, they would currently cost about $36,000 each.

Once the technical hurdles are crossed, hydrogen's huge price tag may still make the technology prohibitive. A recent analysis by the Department of Energy projected that a supply network adequate for even 40 percent of the light-duty fleet could cost more than $500 billion. And that leads to a classic chicken-and-egg problem: How do you get millions of Americans to buy hydrogen-powered vehicles before there's an infrastructure in place to refuel them? And how do you get energy companies to build that infrastructure before there's a potential customer base?

"Companies are not willing to invest if they don't think there's going to be a market," says Daniel Sperling, director of the Institute of Transportation Studies at UC Davis. "The government has to be behind it. There has to be leadership."

There's reason to hope the technology will advance even without much government involvement. Hydrogen fuel cells already replace batteries in niche equipment, such as TV cameras and forklifts, and provide power at remote locations, such as at cellphone towers. They even power the police station in New York's Central Park. As these applications continue to develop, they will force advances in technology that will make hydrogen vehicles more feasible. Even then, hydrogen might make the most sense for fleet vehicles that don't require widespread infrastructure for service and refueling.

Ultimately, hydrogen may be just one part of a whole suite of energy alternatives. Any one of them will involve investing heavily in new infrastructure. Though the price tag will be steep, we can't afford oil's environmental, economic and political drawbacks any longer.

Where Will the Hydrogen Come From?

President Bush's Hydrogen Fuel Initiative calls for replacing fossil fuels used in passenger cars by 2040. This would require 150 million tons of hydrogen anually. Here's what it would take to reach that goal with any one technology.

	NATURAL GAS	NUCLEAR	SOLAR	WIND	BIOMASS
	Gas station-size facilities using steam reformation	Very High Temperature Reactors providing heat for electrolysis	Photovoltaic systems providing electricity for electrolysis	Turbines producing electricity for electrolysis,	Gasification plants using steam reformation

		or for thermochemical cycles	with 10% efficiency	assuming they operate at 30% capacity	
Raw Materials Required	15.9 million cu. ft. of natural gas — only a fraction of current U.S. annual consumption	240,000 tons of unenriched uranium, five times today's global production	2500 kilowatt-hours of sun per square meter per year, found in the Southwestern states of the Sun Belt	7 meters per second average wind speed, typically found in many parts of the country	1.5 billion tons of dry biomass (initially byproducts such as peanut shells, then concentrated crops)
Infrastructure	777,000 facilities; though a more likely scenario would include a mix of larger central production plants	2000 600-megawatt next-generation nuclear power plants; only 103 nuclear power plants operate in the States today	113 million 40-kilowatt systems, covering 50% of more than 300 million acres — an area three size the size of Nevada	1 million 2-megawatt wind turbines, covering 5% of 120 million acres, or an area larger than California	3300 gasification plants, and up to 113.4 million acres — or 11% of U.S. farmland — dedicated to growing the biomass
Total Cost	$1 trillion	$840 billion	$22 trillion	$3 trillion	$565 billion
Price Per GGE (Gallon of Gas Equivalent)	$3.00	$2.50	$9.50	$3.00	$1.90
CO2 Emissions measured in tons	300 million	0	0	0	600 million*
	*Zero net emissions because crops pull CO2 from the air. **90% will be cap stored underground.				

Time Frame	There are four fueling stations that now produce hydrogen from natural gas.	The first Very High Temperature Reactor in the U.S. will be built at Idaho National Laboratory in 2021.	Honda built an experimental solar-powered hydrogen refueling station at its lab in California in 2001.	A 100-kilowatt turbine is now being built at the National Renewable Energy Lab in Colorado.	Government funded bio-mass research will be transferred to private industry in 2015.	[illegible]