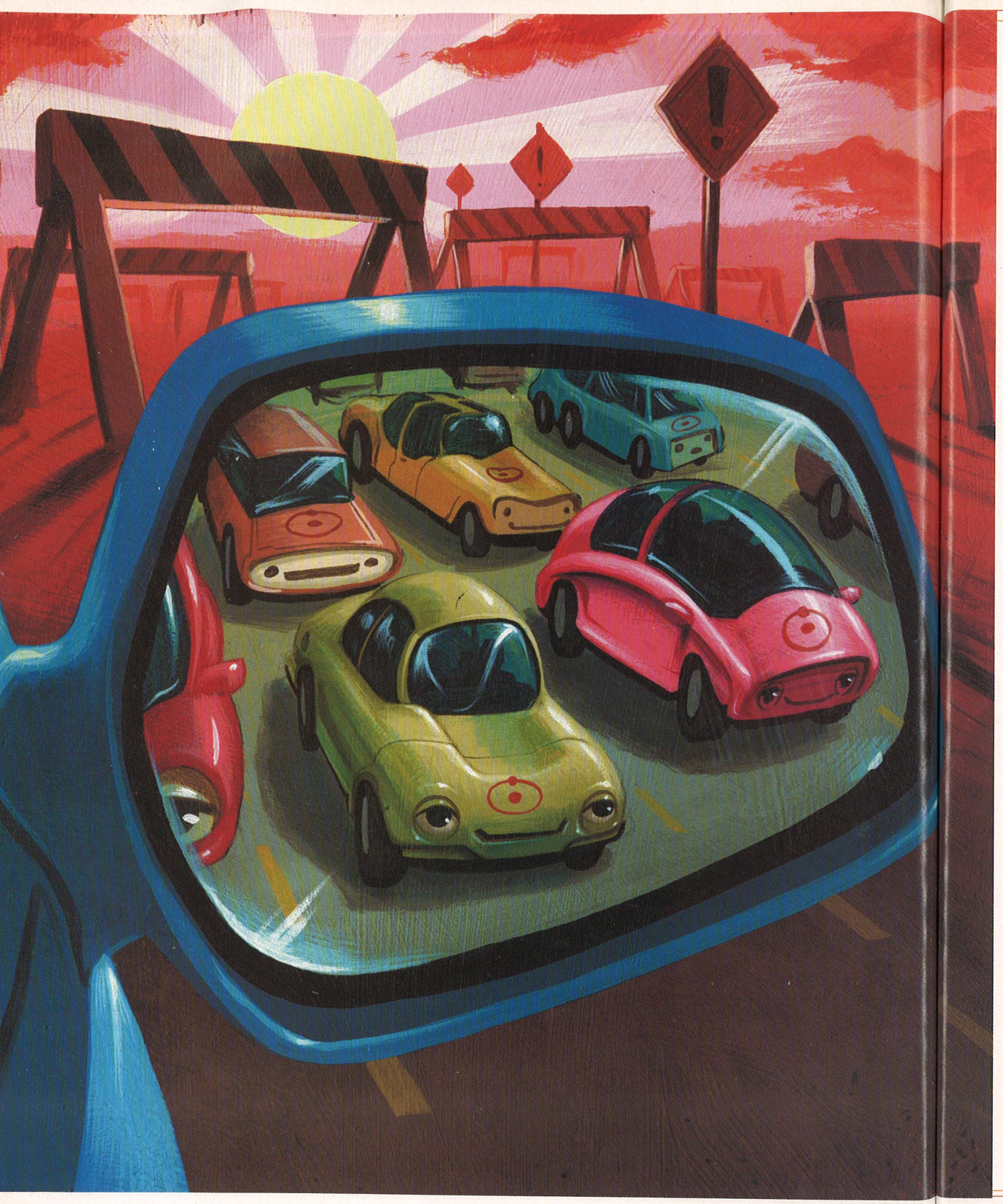


WARNING: THE HYDROGEN ECONOMY MAY BE MORE DISTANT THAN IT APPEARS

Nine myths and misconceptions, and the truth about why hydrogen-powered cars aren't just around the corner

In the presidential campaign of 2004, Bush and Kerry managed to find one piece of common ground: Both spoke glowingly of a future powered by fuel cells. Hydrogen would free us from our dependence on fossil fuels and would dramatically curb emissions of air pollutants, including carbon dioxide, the gas chiefly blamed for global warming. The entire worldwide energy market would evolve into a "hydrogen economy" based on clean, abundant power. Auto manufacturers and environmentalists alike happily rode the bandwagon, pointing to hydrogen as the next big thing in U.S. energy policy. Yet the truth is that we aren't much closer to a commercially viable hydrogen-powered car than we are to cold fusion or a cure for cancer. This hardly surprises engineers, fuel cell manufacturers and policymakers, who have known all along that the technology has been hyped, perhaps to its detriment, and that the public has been misled about what Howard Coffman, editor of *fuelcell-info.com*, describes as the "undeniable realities of the hydrogen economy." These experts are confident that the hydrogen economy will arrive—someday. But first, they say, we have to overcome daunting technological, financial and political roadblocks. Herewith, our checklist of misconceptions and doubts about hydrogen and the exalted fuel cell.

BY MICHAEL BEHAR

ILLUSTRATIONS BY JEFF SOTO

1 HYDROGEN IS AN ABUNDANT FUEL

TRUE, HYDROGEN IS THE MOST COMMON ELEMENT in the universe; it's so plentiful that the sun consumes 600 million tons of it every second. But unlike oil, vast reservoirs of hydrogen don't exist here on Earth. Instead, hydrogen atoms are bound up in molecules with other elements, and we must expend energy to extract the hydrogen so it can be used in fuel cells. We'll never get more energy out of hydrogen than we put into it.

"Hydrogen is a currency, not a primary energy source," explains Geoffrey Ballard, the father of the modern-day fuel cell and co-founder of Ballard Power Systems, the world's leading fuel-cell developer. "It's a means of getting energy from where you created it to where you need it."

2 HYDROGEN FUEL CELLS WILL END GLOBAL WARMING

UNLIKE INTERNAL COMBUSTION ENGINES, HYDROGEN fuel cells do not emit carbon dioxide. But extracting hydrogen from natural gas, today's primary source, does. And wresting hydrogen from water through electrolysis takes tremendous amounts of energy. If that energy comes from power plants burning fossil fuels, the end product may be clean hydrogen, but the process used to obtain it is still dirty.

Once hydrogen is extracted, it must be compressed and transported, presumably by machinery and vehicles that in the early stages of a hydrogen economy will be running on fossil fuels. The result: even more CO_2. In fact, driving a fuel cell car with hydrogen extracted from natural gas or water could pro-

duce a net increase of CO_2 in the atmosphere. "People say that hydrogen cars would be pollution-free," observes University of Calgary engineering professor David Keith. "Lightbulbs are pollution-free, but power plants are not."

In the short term, nuclear power may be the easiest way to produce hydrogen without pumping more carbon dioxide into the atmosphere. Electricity from a nuclear plant would electrolyze water—splitting H_2O into hydrogen and oxygen. Ballard champions the idea, calling nuclear power "extremely important, unless we see some other major breakthrough that none of us has envisioned."

Critics counter that nuclear power creates long-term waste problems and isn't economically competitive. An exhaustive industry analysis entitled "The Future of Nuclear Power," written last year by 10 professors from the Massachusetts Institute of Technology and Harvard University, concludes that "hydrogen produced by electrolysis of water depends on low-cost nuclear power." As long as electricity from nuclear power costs more than electricity from other sources, using that energy to make hydrogen doesn't add up.

3 THE HYDROGEN ECONOMY CAN RUN ON RENEWABLE ENERGY

PERFORM ELECTROLYSIS WITH RENEWABLE ENERGY, such as solar or wind power, and you eliminate the pollution issues associated with fossil fuels and nuclear power. Trouble is, renewable sources can provide only a small fraction of the energy that will be required for a full-fledged hydrogen economy.

From 1998 to 2003, the generating capacity of wind power increased 28 percent in the U.S. to 6,374 megawatts, enough for roughly 1.6 million homes. The wind industry expects to meet 6 percent of the country's electricity needs by 2020. But economist Andrew Oswald of the University of Warwick in England calculates that converting every vehicle in the U.S. to hydrogen power would require the electricity output of a million wind turbines—enough to cover half of California. Solar panels would likewise require huge swaths of land.

Water is another limiting factor for hydrogen production, especially in the sunny regions most suitable for solar power. According to a study done by the World Resources Institute, a Washington, D.C.–based nonprofit organization, fueling a hydrogen economy with electrolysis would require 4.2 trillion gallons of water annually—roughly the amount that flows over Niagara Falls every three months. Overall, U.S. water consumption would increase by about 10 percent.

4 HYDROGEN GAS LEAKS ARE NOTHING TO WORRY ABOUT

HYDROGEN GAS IS ODORLESS AND COLORLESS, and it burns almost invisibly. A tiny fire may go undetected at a leaky fuel pump until your pant leg goes up in flames. And it doesn't take much to set compressed hydrogen gas alight. "A cellphone or a lightning storm puts out enough static discharge to ignite hydrogen," claims Joseph Romm, author of *The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate* and founder of the Center for Energy and Climate Solutions in Arlington, Virginia.

A fender bender is unlikely to spark an explosion, because carbon-fiber-reinforced hydrogen tanks are virtually indestructible. But that doesn't eliminate the danger of leaks elsewhere in what will eventually be a huge network of refineries, pipelines and fueling stations. "The obvious pitfall is that hydrogen is a gas, and most of our existing petrochemical sources are liquids," says Robert Uhrig, professor emeritus of nuclear engineering at the University of Tennessee and former vice president of Florida Power & Light. "The infrastructure required to support high-pressure gas or cryogenic liquid hydrogen is much more complicated. Hydrogen is one of those things that people have great difficulty confining. It tends to go through the finest of holes."

To calculate the effects a leaky infrastructure might have on our atmosphere, a team of researchers from the California Institute of Technology and the Jet Propulsion Laboratory in Pasadena, California, looked at statistics for accidental industrial hydrogen and natural gas leakage—estimated at 10 to 20 percent of total volume—and then predicted how much leakage might occur in an economy in which everything runs on hydrogen. Result: The amount of hydrogen in the atmosphere would be four to eight times as high as it is today.

The Caltech study "grossly overstated" hydrogen leakage, says Assistant Secretary David Garman of the Department of Energy's Office of Energy Efficiency and Renewable

4.2 TRILLION GALLONS

The amount of water that would be required annually to make enough hydrogen through electrolysis to power the U.S. economy. That's roughly the amount of water that flows over Niagara Falls every three months.

Energy. But whatever its volume, hydrogen added to the atmosphere will combine with oxygen to form water vapor, creating noctilucent clouds—those high, wispy tendrils you see at dawn and dusk. The increased cloud cover could accelerate global warming.

5 CARS ARE THE NATURAL FIRST APPLICATION FOR HYDROGEN FUEL CELLS

"AN ECONOMICALLY SANE, COST-EFFECTIVE ATTACK on the climate problem wouldn't start with cars," David Keith says. Cars and light trucks contribute roughly 20 percent of the carbon dioxide emitted in the U.S., while power plants burning fossil fuels are responsible for more than 40 percent of CO_2 emissions. Fuel cells designed for vehicles must cope with harsh conditions and severe limitations on size and weight.

A better solution to global warming might be to hold off building hydrogen cars, and instead harness fuel cells to generate electricity for homes and businesses. Plug Power, UTC, FuelCell Energy and Ballard Power Systems already market stationary fuel-cell generators. Plug Power alone has 161 systems in the U.S., including the first fuel-cell-powered McDonald's. Collectively, however, the four companies have a peak generating capacity of about 69 megawatts, less than 0.01 percent of the total 944,000 megawatts of U.S. generating capacity.

6 THE U.S. IS COMMITTED TO HYDROGEN, POURING BILLIONS INTO R&D

CONSIDER THIS: PRESIDENT GEORGE W. BUSH promised to spend $1.2 billion on hydrogen. Yet he allotted $1.5 billion to promote "healthy marriages." The monthly tab for the war in Iraq is $3.9 billion—a total of $121 billion through last September. In 2004 the Department of Energy spent more on nuclear and fossil fuel research than on hydrogen.

The federal government's FreedomCAR program, which funds hydrogen R&D in conjunction with the big three American carmakers, requires that the companies demonstrate a hydrogen-powered car by 2008—but not that they sell one.

"If you are serious about [hydrogen], you have to commit a whole lot more money," contends Guenter Conzelmann, deputy director of the Center for Energy, Environmental and Economic Systems Analysis at Argonne National Laboratory near Chicago. Conzelmann develops computer models to help the energy industry make predictions about the cost of implementing new technology. His estimate for building a hydrogen economy: more than $500 billion, and that's if 60 percent of Americans continue to drive cars with internal combustion engines.

Shell, ExxonMobil and other oil companies are unwilling to invest in production, distribution, fueling facilities and storage if there are just a handful of hydrogen cars on the road. Nor will automakers foot the bill and churn out thousands of hydrogen cars if drivers have nowhere to fill them up. Peter Devlin, head of the Department of Energy's hydrogen-production research group, says, "Our industry partners have told us that unless a fourth to a third of all refueling stations in the U.S. offer hydrogen, they won't be willing to take a chance on fuel cells."

To create hydrogen fueling stations, California governor Arnold Schwarzenegger, who drives a Hummer, has championed the Hydrogen Highway Project. His plan is to erect 150 to 200 stations—at a cost of at least $500,000 each—along the state's major highways by the end of the decade. So that's one state. Now what about the other 100,775 filling stations in the rest of the U.S.? Retrofitting just 25 percent of those with hydrogen fueling systems would cost more than $13 billion.

7 IF ICELAND CAN DO IT, SO CAN WE

ICELAND'S FIRST HYDROGEN FUELING STATION IS already operating on the outskirts of Reykjavík. The hydrogen, which powers a small fleet of fuel cell buses, is produced onsite from electrolyzed tap water. Meanwhile the recently formed Icelandic New Energy—a consortium that includes automakers, Royal Dutch/Shell and the Icelandic power company Norsk Hydro—is planning to convert the rest of the island nation to a hydrogen system.

Impressive, yes. But 72 percent of Iceland's electricity comes from geothermal and hydroelectric power. With so much readily available clean energy, Iceland can electrolyze water with electricity directly from the national power grid. This type of setup is impossible in the U.S., where only about 15 percent of grid electricity comes from geothermal and hydroelectric sources, while 71 percent is generated by burning fossil fuels.

Another issue is the sheer scale of the system. It could take as few as 16 hydrogen fueling stations to enable Icelanders to drive fuel cell cars anywhere in the country. At close to 90 times the size of Iceland, the U.S. would require a minimum of 1,440 fueling stations. This assumes that stations would be strategically placed to collectively cover the entire U.S. with no overlap and that everyone knows where to find the pumps.

8 MASS PRODUCTION WILL MAKE HYDROGEN CARS AFFORDABLE

SIMPLY MASS-PRODUCING FUEL CELL CARS WON'T necessarily slash costs. According to Patrick Davis, the former leader of the Department of Energy's fuel cell research team, "If you project today's fuel cell technologies into high-volume production—about 500,000 vehicles a year—the cost is still up to six times too high."

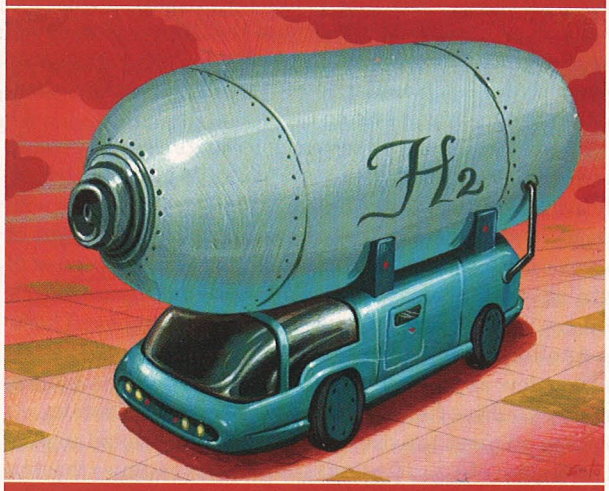
Raj Choudhury, operations manager for the General Motors fuel cell program, claims that GM will have a commercial fuel cell vehicle ready by 2010. Others are doubtful. Ballard says that first there needs to be a "fundamental engineering rethink" of the proton exchange membrane (PEM) fuel cell, the type being developed for automobiles, which still cannot compete with the industry standard for internal combustion engines—a life span of 15 years, or about 170,000 driving miles. Because of membrane deterioration, today's PEM fuel cells typically fail during their first 2,000 hours of operation.

Ballard insists that his original PEM design was merely a prototype. "Ten years ago I said it was the height of engineering arrogance to think that the architecture and geometry we chose to demonstrate the fuel cell in automobiles would be the best architecture and geometry for a commercial automobile," he remarks. "Very few people paid attention to that statement. The truth is that the present geometry isn't getting the price down to where it is com-

mercial. It isn't even entering into the envelope that will allow economies of scale to drive the price down."

In the short term, conventional gasoline-burning vehicles will be replaced by gas-electric hybrids, or by vehicles that burn clean diesel, natural gas, methanol or ethanol. Only later will hydrogen cars make sense, economically and environmentally. "Most analysts think it will take several decades for hydrogen to make a large impact, assuming hydrogen technologies reach their goals," notes Joan Ogden, an associate professor of environmental science and policy at the University of California at Davis and one of the world's leading researchers of hydrogen energy.

10,000 POUNDS PER SQUARE INCH



The amount of pressure hydrogen would have to be under to power a car for at least 300 miles between fill-ups. Even at such high pressures, hydrogen would take up four times the space that gasoline does.

9 FUEL CELL CARS CAN DRIVE HUNDREDS OF MILES ON A SINGLE TANK OF HYDROGEN

A GALLON OF GASOLINE CONTAINS ABOUT 2,600 times the energy of a gallon of hydrogen. If engineers want hydrogen cars to travel at least 300 miles between fill-ups—the automotive-industry benchmark—they'll have to compress hydrogen gas to extremely high pressures: up to 10,000 pounds per square inch.

Even at that pressure, cars would need huge fuel tanks. "High-pressure hydrogen would take up four times the volume of gasoline," says JoAnn Milliken, chief engineer of the Department of Energy's Office of Hydrogen, Fuel Cells and Infrastructure Technologies.

Liquid hydrogen works a bit better. GM's liquid-fueled HydroGen3 goes 250 miles on a tank roughly double the size of that in a standard sedan. But the car must be driven every day to keep the liquid hydrogen chilled to –253 degrees Celsius—just 20 degrees above absolute zero and well below the surface temperature of Pluto—or it boils off. "If your car sits at the airport for a week, you'll have an empty tank when you get back," Milliken says.

See how a hydrogen fuel cell works at **popsci.com/fuelcell**.

? IF NOT HYDROGEN, THEN *WHAT?*

THE NEAR-FUTURE PROSPECTS FOR A HYDROGEN economy are dim, concludes *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, a major government-sponsored study published last February by the National Research Council. Representatives from ExxonMobil, Ford, DuPont, the Natural Resources Defense Council and other stakeholders contributed to the report, which urges lawmakers to legislate tougher tailpipe-emission standards and to earmark additional R&D funding for renewable energy and alternative fuels. It foresees "major hurdles on the path to achieving the vision of the hydrogen economy" and recommends that the Department of Energy "keep a balanced portfolio of R&D efforts and continue to explore supply-and-demand alternatives that do not depend on hydrogen."

Of course, for each instance where the study points out how hydrogen falls short, there are scores of advocates armed with data to show how it can succeed. Physicist Amory Lovins, who heads the Rocky Mountain Institute, a think tank in Colorado, fastidiously rebuts the most common critiques of hydrogen with an armada of facts and figures in his widely circulated white paper "Twenty Hydrogen Myths." But although he's a booster of hydrogen, Lovins is notably pragmatic. "A lot of silly things have been written both for and against hydrogen," he says. "Some sense of reality is lacking on both sides." He believes that whether the hydrogen economy arrives at the end of this decade or closer to midcentury, interim technologies will play a signal role in the transition.

The most promising of these technologies is the gas-electric hybrid vehicle, which uses both an internal combustion engine and an electric motor, switching seamlessly between the two to optimize gas mileage and engine efficiency. U.S. sales of hybrid cars have been growing steadily, and the 2005 model year saw the arrival of the first hybrid SUVs—the Ford Escape, Toyota Highlander and Lexus RX400h.

Researchers sponsored by the FreedomCAR program are also investigating ultralight materials—plastics, fiberglass, titanium, magnesium, carbon fiber—and developing lighter engines made from aluminum and ceramic materials. These new materials could help reduce vehicle power demands, bridging the cost gap between fossil fuels and fuel cells.

Most experts agree that there is no silver bullet. Instead the key is developing a portfolio of energy-efficient technologies that can help liberate us from fossil fuels and ease global warming. "If we had a wider and more diverse set of energy sources, we'd be more robust, more stable," says Jonathan Pershing, director of the Climate, Energy and Pollution Program at the World Resources Institute. "The more legs your chair rests on, the less likely it is to tip over."

Waiting for hydrogen to save us isn't an option. "If we fail to act during this decade to reduce greenhouse gas emissions, historians will condemn us," Romm writes in *The Hype about Hydrogen*. "And they will most likely be living in a world with a much hotter and harsher climate than ours, one that has undergone an irreversible change for the worse." ■

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