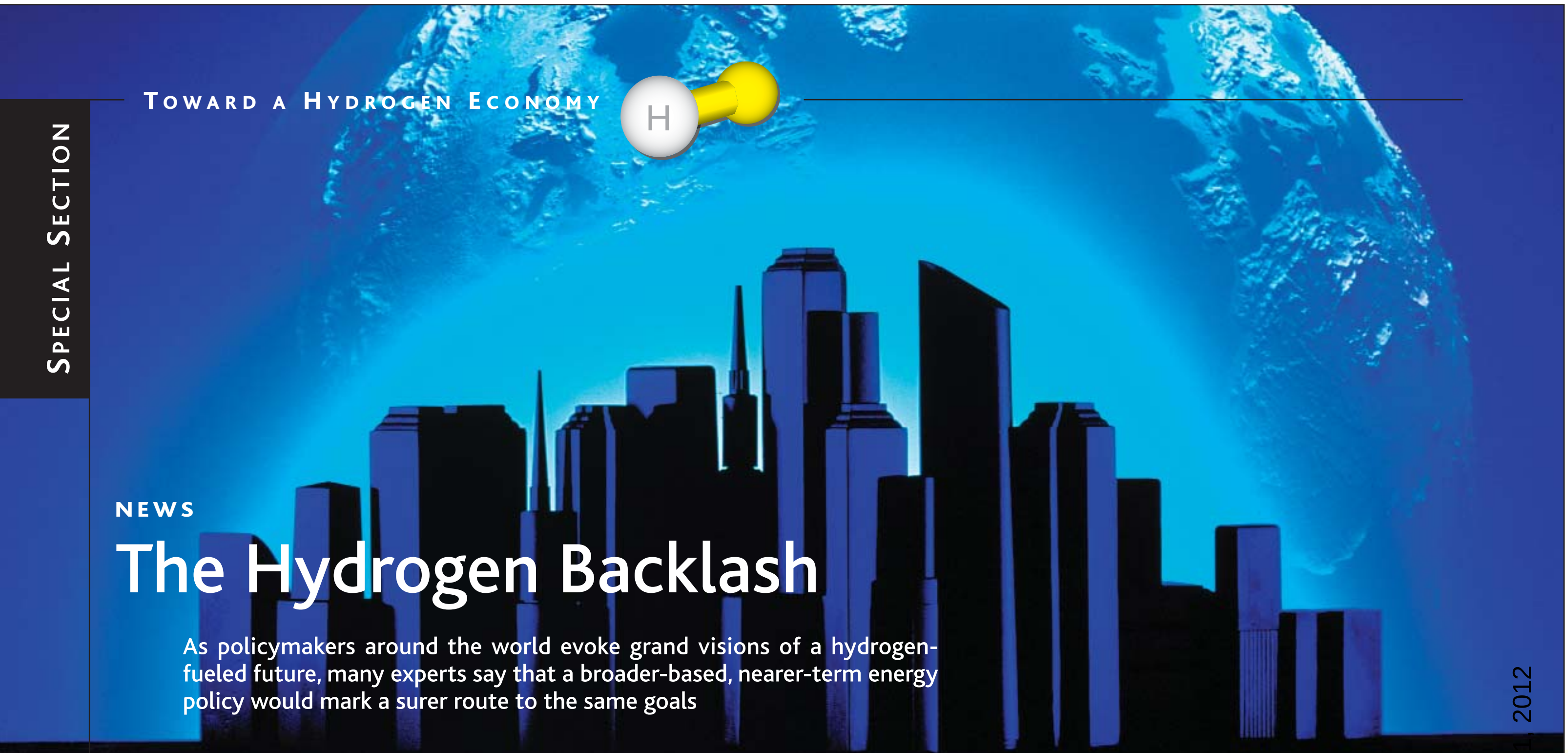


News

The Hydrogen Backlash

As policymakers around the world evoke grand visions of a hydrogen-fueled future, many experts say that a broader-based, nearer-term energy policy would mark a surer route to the same goals

In the glare of a July afternoon, the HydroGen3 minivan threaded through the streets near Capitol Hill. As a *Science* staffer put it through its stop-and-go paces, 200 fuel cells under the hood of the General Motors prototype inhaled hydrogen molecules, stripped off their electrons, and fed current to the electric engine. The only emissions: a little extra heat and humidity. The result was a smooth, eerily quiet ride—one that, with H3's priced at $1 million each, working journalists won't be repeating at their own expense anytime soon.

Hydrogen-powered vehicles may be rareties on Pennsylvania Avenue, but in Washington, D.C., and other world capitals they and their technological kin are very much on people's minds. Switching from fossil fuels to hydrogen could dramatically reduce urban air pollution, lower dependence on foreign oil, and reduce the buildup of greenhouse gases that threaten to trigger severe climate change.

With those perceived benefits in view, the United States, the European Union, Japan, and other governments have sunk billions of dollars into hydrogen initiatives aimed at revving up the technology and propelling it to market. Car and energy companies are pumping billions more into building demonstration fleets and hydrogen fueling stations. Many policymakers see the move from oil to hydrogen as manifest destiny, challenging but inevitable. In a recent speech, Spencer Abraham, the U.S. secretary of energy, said such a transformation has "the potential to change our country on a scale of the development of electricity and the internal combustion engine."

The only problem is that the bet on the hydrogen economy is at best a long shot. Recent reports from the U.S. National Academy of Sciences (NAS) and the American Physical Society (APS) conclude that researchers face daunting challenges in finding ways to produce and store hydrogen, convert it to electricity, supply it to consumers, and overcome vexing safety concerns. Any of those hurdles could block a broad-based changeover. Solving them simultaneously is "a very tall order," says Mildred Dresselhaus, a physicist at the Massachusetts Institute of Technology (MIT), who has served on recent hydrogen review panels with the U.S. Department of Energy (DOE) and APS as well as serving as a reviewer for the related NAS report.

As a result, the transition to a hydrogen economy, if it comes at all, won't happen soon. "It's very, very far away from substantial deployed impact," says Ernest Moniz, a physicist at MIT and a former undersecretary of energy at DOE. "Let's just say decades, and I don't mean one or two."

In the meantime, some energy researchers complain that, by skewing research toward costly large-scale demonstrations of technology well before it's ready for market, governments risk repeating a pattern that has sunk previous technologies such as synfuels in the 1980s. By focusing research on technologies that aren't likely to have a measurable impact until the second half of the century, the current hydrogen push fails to address the growing threat from greenhouse gas emissions from fossil fuels. "There is starting to be some backlash on the hydrogen economy," says Howard Herzog, an MIT chemical engineer. "The hype has been way overblown. It's just not thought through."

A perfect choice?

Almost everyone agrees that producing a viable hydrogen economy is a worthy long-term goal. For starters, worldwide oil production is expected to peak within the next few decades, and although supplies will remain plentiful long afterward, oil prices are expected to soar as international markets view the fuel as increasingly scarce. Natural gas production is likely to peak a couple of decades after oil. Coal, tar sands, and other fossil fuels should remain plentiful for at least another century. But these dirtier fuels carry a steep environmental cost: Generating electricity from coal instead of natural gas, for example, releases twice as much carbon dioxide (CO_2). And in order to power vehicles, they must be

CREDIT: (TOP TO BOTTOM) GEORGE B. DIEBOLD/CORBIS; PHOTO COURTESY OF GM CORP.

converted to a liquid or gas, which requires energy and therefore raises their cost.

Even with plenty of fossil fuels available, it's doubtful we'll want to use them all. Burning fossil fuels has already increased the concentration of CO_2 in the atmosphere from 280 to 370 parts per million (ppm) over the past 150 years. Unchecked, it's expected to pass 550 ppm this century, according to New York University physicist Martin Hoffert and colleagues in a 2002 *Science* paper (*Science*, 1 November 2002, p. 981). "If sustained, [it] could eventually produce global warming comparable in magnitude but opposite in sign to the global cooling of the last Ice Age," the authors write. Development and population growth can only aggravate the problems.

On the face of it, hydrogen seems like the perfect alternative. When burned, or oxidized in a fuel cell, it emits no pollution, including no greenhouse gases. Gram for gram, it releases more energy than any other fuel. And as a constituent of water, hydrogen is all around us. No wonder it's being touted as the clean fuel of the future and the answer to modern society's addiction to fossil fuels. In April 2003, *Wired* magazine laid out "How Hydrogen Can Save America." Environmental gadfly Jeremy Rifkin has hailed the hydrogen economy as the next great economic revolution. And General Motors has announced plans to be the first company to sell 1 million hydrogen fuel cell cars by the middle of the next decade.

Last year, the Bush Administration plunged in, launching a 5-year, \$1.7 billion initiative to commercialize hydrogen-powered cars by 2020. In March, the European Commission launched the first phase of an expected 10-year, €2.8 billion public-private partnership to develop hydrogen fuel cells. Last year, the Japanese government nearly doubled its fuel cell R&D budget to \$268 million. Canada, China, and other countries have mounted efforts of their own. Car companies have already spent billions of dollars trying to reinvent their wheels—or at least their engines—to run on hydrogen: They've turned out nearly 70 prototype cars and trucks as well as dozens of buses. Energy and car companies have added scores of hydrogen fueling stations worldwide, with many more on the drawing boards (see p. 964). And the effort is still gaining steam.

The problem of price

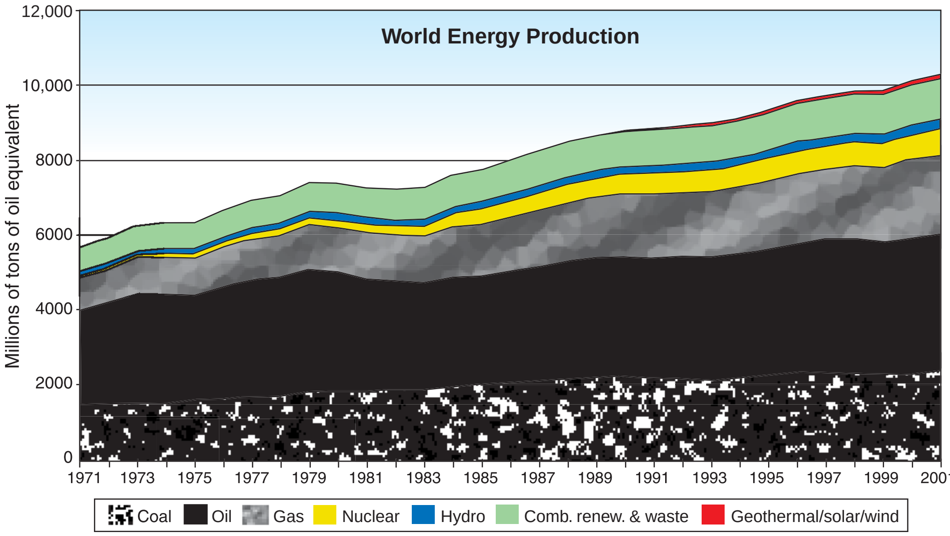
Still, despite worthwhile goals and good intentions, many researchers and energy experts say current hydrogen programs fall pitifully short of what's needed to bring a hydrogen economy to pass. The world's energy infrastructure is too vast, they say, and the challenges of making hydrogen technology competitive with fossil fuels too daunting unless substantially more funds are added to the pot. The current initiatives are just "a start," Dresselhaus says. "None of the reports say it's impossible," she adds. However, Dresselhaus says, "the problem is very difficult no matter how you slice it."

Economic and political difficulties abound, but the most glaring barriers are technical. At the top of the list: finding a simple and cheap way to produce hydrogen. As is often pointed out, hydrogen is not a fuel in itself, as oil and coal are. Rather, like electricity, it's an energy carrier that must be generated using another source of power. Hydrogen is the most common element in the universe. But on Earth, nearly all of it is bound to other elements in molecules, such as hydrocarbons and water. Hydrogen atoms must be split off these molecules to generate dihydrogen gas (H_2), the form it needs to be in to work in most fuel cells. These devices then combine hydrogen and oxygen to make water and liberate electricity in the process. But every time a fuel is converted from one source, such as oil, to another, such as electricity or hydrogen, it costs energy and therefore money.

Today, by far the cheapest way to produce hydrogen is by using steam and catalysts to break down natural gas into H_2 and CO_2. But although the technology has been around for decades, current steam reformers are only 85% efficient, meaning that 15% of the energy in natural gas is lost as waste heat during the reforming process. The upshot, according to Peter Devlin, who runs a hydrogen production program at DOE, is that it costs \$5 to produce the amount of hydrogen that releases as much energy as a gallon of gasoline. Current techniques for liberating hydrogen from coal, oil, or water are even less efficient. Renewable energy such as solar and wind power can also supply electricity to split water, without generating CO_2. But those technologies are even more expensive. Generating electricity with solar power, for example, remains 10 times more expensive than doing so with a coal plant. "The energy in hydrogen will always be more expensive than the sources used to make it," said Donald Huberts, chief executive officer of Shell Hydrogen, at a hearing before the U.S. House Science Committee in March. "It will be competitive only by its other benefits: cleaner air, lower greenhouse gases, et cetera."

The good news, Devlin says, is that production costs have been coming down, dropping about \$1 per gallon (\$0.25/liter) of gasoline equivalent over the past 3 years. The trouble is that DOE's own road map projects that drivers will buy hydrogen-powered cars only if the cost of the fuel drops to \$1.50 per gallon of gasoline equivalent by 2010 and even lower in the years beyond. "The easy stuff is over," says Devlin. "There are going to have to be some fundamental breakthroughs to get to \$1.50."

There are ideas on the drawing board. In addition to stripping hydrogen from fossil fuels, DOE and other funding agencies are backing innovative research ideas to produce hydrogen with algae, use sunlight and catalysts to split water molecules directly, and siphon hydrogen from agricultural waste and other types of "biomass." Years of research in all of these areas, however, have yet to yield decisive progress.



Over a barrel. The world is growing increasingly dependent on fossil fuels.

SOURCE: INTERNATIONAL ENERGY AGENCY

To have and to hold

If producing hydrogen cheaply has researchers scratching their heads, storing enough of it on board a car has them positively stymied. Because hydrogen is the lightest element, far less of it can fit into a given volume than other fuels. At room temperature and pressure, hydrogen takes up roughly 3000 times as much space as gasoline containing the same amount of energy. That means storing enough of it in a fuel tank to drive 300 miles (483 kilometers)—DOE's benchmark—requires either compressing it, liquefying it, or using some other form of advanced storage system.

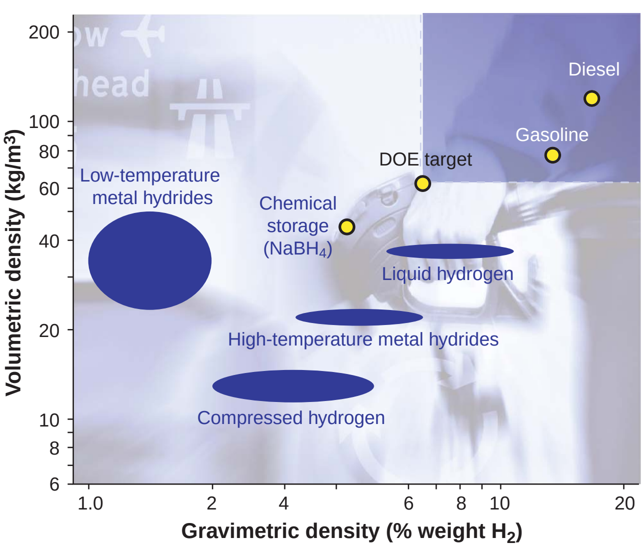
Unfortunately, none of these solutions is up to the task of carrying a vehicle 300 miles on a tank. Nearly all of today's prototype hydrogen vehicles use compressed gas. But these are still bulky. Tanks pressurized to 10,000 pounds per square inch (70 MPa) take up to eight times the volume of a current gas tank to store the equivalent amount of fuel. Because fuel cells are twice as efficient as gasoline internal combustion engines, they need fuel tanks four times as large to propel a car the same distance.

Liquid hydrogen takes up much less room but poses other problems. The gas liquefies at –253°C, just a few degrees above absolute zero. Chilling it to that temperature requires about 30% of the energy in the hydrogen. And the heavily insulated tanks needed to keep liquid fuel from boiling away are still larger than ordinary gasoline tanks.

Other advanced materials are also being investigated to store hydrogen, such as carbon nanotubes, metal hydrides, and substances such as sodium borohydride that produce hydrogen by means of a chemical reaction. Each material has shown some promise. But for now, each still has fatal drawbacks, such as requiring high temperature or pressures, releasing the hydrogen too slowly, or requiring complex and time-consuming materials recycling. As a result, many experts are pessimistic. A report last year from DOE's Basic Energy Sciences Advisory Committee concluded: "A new paradigm is required for the development of hydrogen storage materials to facilitate a hydrogen economy." Peter Eisenberger, vice provost of Columbia University's Earth Institute, who chaired the APS report, is even more blunt. "Hydrogen storage is a potential showstopper," he says.

Breakthroughs needed

Another area in need of serious progress is the fuel cells that convert hydrogen to electricity. Fuel cells have been around since the 1800s and have been used successfully for decades to power spacecraft. But their high cost and other drawbacks have kept them from being used for everyday applications such as cars. Internal combustion engines typically cost $30 for each kilowatt of power they produce. Fuel cells, which are loaded with precious-metal catalysts, are 100 times more expensive than that.



Showstopper? Current hydrogen storage technologies fall short of both the U.S. Department of Energy target and the performance of petroleum.

If progress on renewable technologies is any indication, near-term prospects for cheap fuel cells aren't bright, says Joseph Romm, former acting assistant secretary of energy for renewable energy in the Clinton Administration and author of a recent book, *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate*. "It has taken wind power and solar power each about twenty years to see a tenfold decline in prices, after major government and private sector investments, and they still each comprise well under 1% of U.S. electricity generation," Romm said in written testimony in March before the House Science Committee reviewing the Administration's hydrogen initiative. "A major technology breakthrough is needed in transportation fuel cells before they will be practical." Various technical challenges—such as making fuel cells rugged enough to withstand the shocks of driving and ensuring the safety of cars loaded with flammable hydrogen gas—are also likely to make hydrogen cars costlier to engineer and slower to win public acceptance.

If they clear their internal technical hurdles, hydrogen fuel cell cars face an obstacle from outside: the infrastructure they need to refuel. If hydrogen is generated in centralized plants, it will have to be trucked or piped to its final destination. But because of hydrogen's low density, it would take 21 tanker trucks to haul the amount of energy a single gasoline truck delivers today, according to a study by Switzerland-based energy researchers Baldur Eliasson and Ulf Bossel. A hydrogen tanker traveling 500 kilometers would devour the equivalent of 40% of its cargo.

Ship the hydrogen as a liquid? Commercial-scale coolers are too energy-intensive for the job, Eliasson and Bossel point out. Transporting hydrogen through long-distance pipelines wouldn't improve matters much. Eliasson and Bossel calculate that 1.4% of the hydrogen flowing through a pipeline would be required to power the compressors needed to pump it for every 150 kilometers the gas must travel. The upshot, Eliasson and Bossel report: "Only 60% to 70% of the hydrogen fed into a pipeline in Northern Africa would actually arrive in Europe."

To lower those energy penalties, some analysts favor making hydrogen at fueling stations or in homes where it will be used, with equipment powered by the existing electricity grid or natural gas. But onsite production wouldn't be cheap, either. Eliasson and Bossel calculate that to supply hydrogen for 100 to 2000 cars per day, an electrolysis-based fueling station would require between 5 and 81 megawatts of electricity. "The generation of hydrogen at filling stations would make a threefold increase of electric power generating capacity necessary," they report. And at least for the foreseeable future, that extra electricity is likely to come from fossil fuels.

Whichever approach wins out, it will need a massive new hydrogen infrastructure to deliver the goods. The 9 million tons of hydrogen (enough to power between 20 million and 30 million cars) that the United States produces yearly for use in gasoline refining and chemical plants pale beside the needs of a full-blown transportation sector. For a hydrogen economy to catch on, the fuel must be available in 30% to 50% of filling stations when mass-market hydrogen cars become available, says Bernard Bulkin, former chief scientist at BP. A recent study by Marianne Mintz and colleagues at Argonne National Laboratory in Illinois found that creating the infrastructure needed to fuel 40% of America's cars would cost a staggering $500 billion or more.

Energy and car companies are unlikely

CREDIT: ADAPTED FROM P. GUAY, *MODÉLISATION MONTE-CARLO DE L'ADSORPTION DE L'HYDROGÈNE DANS LES NANOSTRUCTURES DE CARBONE*, INRS-EMT, MONTRÉAL, 2003; (IMAGE) ROYALTY-FREE/CORBIS

to spend such sums unless they know mass-produced hydrogen vehicles are on the way. Carmakers, however, are unlikely to build fleets of hydrogen vehicles without stations to refuel them. "We face a 'chicken and egg' problem that will be difficult to overcome," said Michael Ramage, a former executive vice president of ExxonMobil Research and Engineering, who chaired the NAS hydrogen report, when the report was released in February.

Stress test

Each of the problems faced by the hydrogen economy—production, storage, fuel cells, safety, and infrastructure—would be thorny enough on its own. For a hydrogen economy to succeed, however, all of these challenges must be solved simultaneously. One loose end and the entire enterprise could unravel. Because many of the solutions require fundamental breakthroughs, many U.S. researchers question their country's early heavy emphasis on expensive demonstration projects of fuel cell cars, fueling stations, and other technologies.

CO_2 free. To be a clean energy technology, hydrogen must be generated from wind, solar, or other carbon-free sources.

To illustrate the dangers of that approach, the APS report cites the fate of synfuels research in the 1970s and '80s. President Gerald Ford proposed that effort in 1975 as a response to the oil crisis of the early 1970s. But declining oil prices in the 1980s and unmet expectations from demonstration projects undermined industrial and congressional support for the technology. For hydrogen, the report's authors say, the "enormous performance gaps" between existing technology and what is needed for a hydrogen economy to take root means that "the program needs substantially greater emphasis on solving the fundamental science problems."

Focusing the hydrogen program on basic research will naturally give it the appropriate long-term focus it deserves, Romm and others believe. In the meantime, they say, the focus should be on slowing the buildup of greenhouse gases. "If we fail to limit greenhouse gas emissions over the next decade—and especially if we fail to do so because we have bought into the hype about hydrogen's near-term prospects—we will be making an unforgivable national blunder that may lock in global warming for the U.S. of 1 degree Fahrenheit [0.56°C] per decade by mid-century," Romm told the House Science Committee in March in written testimony.

To combat the warming threat, funding agencies should place a near-term priority on promoting energy efficiency, research on renewables, and development of hybrid cars, critics say. After all, many researchers point out, as long as hydrogen for fuel cell cars is provided from fossil fuels, much the same environmental benefits can be gained by adopting hybrid gasoline-electric and advanced diesel engines. As MIT chemist and former DOE director of energy research John Deutch and colleagues point out on page 974, hybrid electric vehicles—a technology already on the market—would improve energy efficiency and reduce greenhouse gas emissions almost as well as fuel cell vehicles that generate hydrogen from an onboard gasoline reformer, an approach that obviates the need for building a separate hydrogen infrastructure.

Near-term help may also come from capturing CO_2 emissions from power and industrial plants and storing them underground, a process known as carbon sequestration (see p. 962). Research teams from around the world are currently testing a variety of schemes for doing that. But the process remains significantly more expensive than current energy. "Until an economical solution to the sequestration problem is found, net reductions in overall CO_2 emissions can only come through advances in energy efficiency and renewable energy," the APS report concludes.

In response to the litany of concerns over making the transition to a hydrogen economy, JoAnn Milliken, who heads hydrogen-storage research for DOE, points out that DOE and other funding agencies aren't promoting hydrogen to the exclusion of other energy research. Renewable energy, carbon sequestration, and even fusion energy all remain in the research mix. Criticism that too much is being spent on demonstration projects is equally misguided, she says, noting that such projects make up only 13% of DOE's hydrogen budget, compared with 85% for basic and applied research. Both are necessary, she says: "We've been doing basic research on hydrogen for a long time. We can't just do one or the other." Finally, she points out, funding agencies have no illusions about the challenge in launching the hydrogen economy. "We never said this is going to be easy," Milliken says. The inescapable truth is that "we need a substitute for gasoline. Gas hybrids are going to improve fuel economy. But they can't solve the problem."

Yet, if that's the case, many energy experts argue, governments should be spending far more money to lower the technical and economic barriers to all types of alternative energy—hydrogen included—and bring it to reality sooner. "Energy is the single most important problem facing humanity today," says Richard Smalley of Rice University in Houston, Texas, a 1996 Nobel laureate in chemistry who has been campaigning for increased energy sciences funding for the last 2 years. Among Smalley's proposals: a 5-cent-per-gallon tax on gasoline in the United States to fund \$10 billion annually in basic energy sciences research. Because of the combination of climate change and the soon-to-be-peaking production in fossil fuels, Smalley says, "it really ought to be the top project in worldwide science right now."

Although not all researchers are willing to wade into the political minefield of backing a gasoline tax, few disagree with his stand. "I think he's right," Dresselhaus says of the need to boost the priority of basic energy sciences research. With respect to the money needed to take a realistic stab at making an alternative energy economy a reality, Dresselhaus says: "Most researchers think there isn't enough money being spent. I think the investment is pretty small compared to the job that has to be done." Even though it sounds like a no-brainer, the hydrogen economy will take abundant gray matter and greenbacks to bring it to fruition.

–ROBERT F. SERVICE

CREDITS: (LEFT TO RIGHT) ML SINIBALDI/CORBIS; PHOTOS.COM