The Hydrogen-Powered Future

Visionary Amory Lovins foresees a world of clean, cheap, reliable energy—and it's a gas.

by Craig Lambert

Amory Lovins (above) leads a globetrotting life, but has lived in the same house (opposite) in Snowmass, Colorado, for more than 20 years. The home is a solar-powered marvel of energy efficiency, and even boasts a tropical garden that grows bananas and papayas within the glassed-in atrium (opposite, above).

Drive up a country road winding between horse pastures, cross a small bridge, then climb a gravel lane, and you can reach a house that seems to defy the laws of physics. About 70,000 visitors have flocked here since it was built in 1982. The curved, 4,000-square-foot sandstone-faced structure in Snowmass, Colorado, has neither heating nor air-conditioning systems, yet is comfortable in temperatures ranging from -47 degrees Fahrenheit to at least 90. Two wood stoves contribute about 1 percent of the heat, but solar energy provides the other 99 percent of space and water heating. The household electric bill would average \$5 per month, except that the solar panels generate five or six times that much electricity; in sunny months, in fact, the house earns money by selling its excess power back to the grid. The walls are "superinsulated" to twice the normal level of effectiveness and the stormdoors and windows do even better: four to six times the norm. The place holds warmth so well that on most nights, "We've heated the house with a 50-watt dog," says the home's energy designer and owner-builder, Amory Lovins '68. "On really cold nights we'd adjust her to a 100-watt dog by throwing a ball."

Here in the Rocky Mountains—Lovins's home is 7,100 feet above sea level—the air is cleaner, the vistas longer and grander than those at lower altitude. Historically, mountains have been a kind of intellectual habitat, an elevated place for meditation, philosophical contemplation, the recognition of large patterns. (Think of Robert Frost in Vermont, or Nietzsche hiking the Swiss Alps.) Perhaps the higher viewpoint helps reveal systemic principles that are invisible at sea level, where the world's major cities, with their commercial bustle, offer narrower horizons.

Lovins fits into the tradition of alpine thought: he thinks big and perceives patterns that most sea-level thinkers have missed. Yet Lovins is anything but detached from the real world of profit margins and balance sheets. He travels constantly—consulting, teaching, advising, and starting projects with such determinedly sea-level enterprises as multinational corporations, real-estate developers, automakers, and the Pentagon.

Lovins has a vision of our energy future: nothing less than shifting our primary fuel from oil to hydrogen. While many doubt hydrogen's potential to power cars, heat homes, and run industries, Lovins declares that the hydrogen economy is coming—it's not a question of *if*, but *when*. His goal is to bring the benefits of hydrogen on-line soon—and he considers that a very viable prospect.

There's a team behind Lovins: his miraculous home doubles as headquarters for Rocky Mountain Institute (RMI), the nonprofit research and consulting firm that he and his former wife, L. Hunter Lovins, founded in 1982 "to foster the efficient and sustainable use of resources." Although RMI is surely a green organization, its client list represents what some environmentalists would call "the enemy"—RMI has worked, for example, with 65 of the Fortune 500. Yet such clients lend RMI's innovative ideas a real-world muscle that many green purists might envy.

Lovins' optimistic futurism contrasts strongly with the dour, "everything-is-going-to-hell" outlook common in environmental politics. Yet even though most energy specialists admire Lovins's brilliance, many question his pragmatism. "Amory is like a mystic, a guru," says Littauer professor of public policy and administration William Hogan, an energy economist at the Kennedy School of Government. "He has been broadly right for a long time. The rub is when you get down to the details—can it be implemented?"

Similar questions were asked of Lovins's intellectual forebear, R. Buckminster Fuller '17 (1895-1983). Both men dropped out of Harvard and set out to change the world, not with political action but through superior design. Unlike political movements, intelligent design has no real opposition: an organization, whatever its ideology, will typically vote with dollars for anything that trims expenses while improving performance. (Fuller made smart design ever smarter, continually finding more efficient solutions: his last geodesic dome, built in 1983, which ornaments a meadow next to an RMI building, is structurally stronger than conventional models, despite using 40 percent less material.)

Lovins endorses Fuller's notion that intelligent design allows one to "do more with less, better, for longer." His personal style is more subdued than the headlong, kinetic energy of Fuller. Yet Lovins's unruffled, almost diffident manner cloaks a first-rate intellect. When he casually drops an astonishing, counterintuitive observation into the conversation, he peers from behind his glasses as if to ask, "How 'bout that?" He often seems amused by his own conclusions, and has a casual deadpan delivery. In his house, a pile of stuffed toy orangutans in the foyer greets visitors; Lovins calls his troop of primates "taxidermically challenged."

The Making of a Visionary

THE PRODIGY LOVINS, who was born in Washington, D.C., and attended public schools in Amherst, Massachusetts, arrived at Harvard in 1964 having already done "most of undergraduate physics," he says. His proactive instincts were already alive: he took a special freshman seminar with the Nobel Prize-winning physicist Edward Purcell that, he says, "was open to all freshmen named Lovins." Due to some knee problems, he left college at the start of his second year and began mountaineering to help strengthen his knees—a pastime that helped crystallize his environmental interests.

Lovins returned to Harvard in 1966, only to drop out permanently after his sophomore year, "largely because I ignored the normal curriculum structure," he explains. "I very much enjoyed my classmates and had some wonderful teachers, like Albert Lord on oral literature and Paul Freund on constitutional law, but I refused to pick a concentration. Chemistry, physics, linguistics, law, and medicine all interested me. Also music—piano and composition. I thought the world had too many specialists and I wanted to be a well-rounded generalist."

Photographs courtesy of the Rocky Mountain Institute

In 1967 Lovins migrated to Magdalen College, Oxford, where "they don't breathe down your neck and let you study a lot of things," he says; two years later he became a don at Merton College, Oxford. He was already interested in energy and land-use problems, and in 1971 wrote and took many of the photographs for a book on an endangered national park in Wales, commissioned by David Brower, president of Friends of the Earth and "the greatest conservationist of the twentieth century," in Lovins's estimate. Lovins went to work full-time for Friends of the Earth, living in London and, when stateside, guiding mountaineering trips in the White Mountains of New Hampshire.

In a celebrated 1976 article in *Foreign Affairs,* "Soft Energy Paths," the 28-year-old Lovins outlined an alternative future where efficient energy use and renewable energy sources like wind, solar power, and biofuels (the "soft path") gradually but steadily supplant a centralized energy system based on fossil and nuclear fuels (the "hard path"). By 1978 he had published six books, consulted widely, and was "active in energy affairs in about 15 countries as synthesist, lobbyist, and cross-pollinator of grapevines," as he wrote in his tenth-reunion report.

In 1979 he married L. Hunter Sheldon, a lawyer, social scientist, and forester; they built their energy-efficient house in Snowmass and in 1982 founded RMI—which has since grown into a $5-million organization with a staff of more than 50 and branches in Boulder and Hawaii. For Lovins, 100-hour workweeks have largely supplanted diversions like music, poetry, squash, and mountain photography. Yet in person he does not appear stressed or harried, even though he is now spread thinly across 50 countries and involved in a dizzying stream of activities. His biography, posted on the RMI website (www.rmi.org) explains that his work "focuses on transforming the automobile, real estate, electricity, water, semiconductor, and several other manufacturing sectors toward advanced resource productivity." Lovins has briefed 18 heads of state and written or coauthored 28 books, the latest of which are *Natural Capitalism* (with Paul Hawken and L. Hunter Lovins), a favorite of former president Bill Clinton, and *Small Is Profitable,* a 2002 *Economist* Book of the Year.

Over the years, the honors have piled on. Lovins has received eight honorary doctorates, a MacArthur Fellowship, and a slew of awards. *Time* named him a Hero for the Planet and *Newsweek* called him "one of the world's most influential energy thinkers." *Car* magazine designated him the twenty-second most powerful person in the global auto industry. Ironically, although Oxford granted Lovins an M.A. by Special Resolution in 1971 (since he was a don), he still lacks an undergraduate degree. In that 1978 reunion report, he wrote that Harvard "is still not freewheeling enough for generalists...still reluctant to prepare its graduates to contribute new insights to great public issues." If so, perhaps he was right to drop out; he has certainly brought new insights to the realm of energy.

The End of the Fossil-fuel Economy

The energy landscape that Lovins sketches begins with much more efficient use of petroleum; he identifies many ways of drastically reducing our oil consumption with no sacrifice in standard of living. Lovins advocates a transformation in *all* the forms of energy we use—not only those that run our cars, but those that heat, light, and power our buildings. Over time, he sees renewable sources like wind and solar energy gradually supplanting fossil fuels. A less familiar but even more powerful piece of the transformation is hydrogen energy, which might eventually make oil and natural gas wells obsolete—and, while they last, more profitable. Hydrogen could potentially generate heat and electricity for homes and office buildings, as well as electrical power to drive a new kind of automobile. Lovins envisions a future in which huge, centralized power plants give way to a decentralized system of small, hydrogen-fed fuel cells making electricity at the point of use. And cars ride cleanly and silently on freeways in a country that doesn't import oil—or use it.

Petroleum, the propellant of the modern economy, entered the energy market only in 1859, when a man wildcatting in Titusville, Pennsylvania, struck oil. But the evolution of technology and the depletion of natural resources are pushing the world's economies beyond oil. Last summer, in a talk at the Given Institute in Aspen, Lovins bluntly declared, "Four oil company chairs and several major automakers have all said we are in the endgame of the oil economy and the beginning of the hydrogen era."

"These are companies that think ahead 50 years," he explains in an interview. "Some, like Shell, have arguably the best foresight of any institution, public or private." Lovins cites a published 2001 Royal Dutch/Shell scenario that calls for oil consumption to stagnate until 2020, then drop steeply. "Whole countries leapfrogging to hydrogen-powered vehicles will displace oil," he says, agreeing with Shell's idea that China could lead the charge. With its huge population, China embodies a strong argument for weaning the world from petroleum. "If the Chinese were all to start driving gasoline-engine cars," Lovins says, "you'd need another Earth."

Any weaning process involves reducing dependence on the prior source of nourishment. The United States, which has 4.5 percent of the world's population, produces 9 percent of the planet's oil and consumes 25 percent, but owns only 2 or 3 percent. Two-thirds of the world's oil reserves are in the Mideast, although Russia, Mexico, and Venezuela are big producers. But petroleum enjoys a different tax status in this country than it does in the rest of world. European nations, for example, tax gasoline far more heavily than the United States does, and therefore retail prices in Europe are typically three to four times those over here.

Lovins sees enormous potential energy savings in efficient use, which could greatly diminish our dependence on petroleum imports. But saving on energy consumption is generally about as popular with Americans as putting aside money; President Ronald Reagan, a onetime General Electric spokesman, famously equated energy conservation with "freezing in the dark." (It has not worked out that way in the warm, well-lit Lovins residence, which is not only super-stingy with fuel, but includes a solar-heated hot tub—and an indoor tropical garden that grows bananas and papayas.)

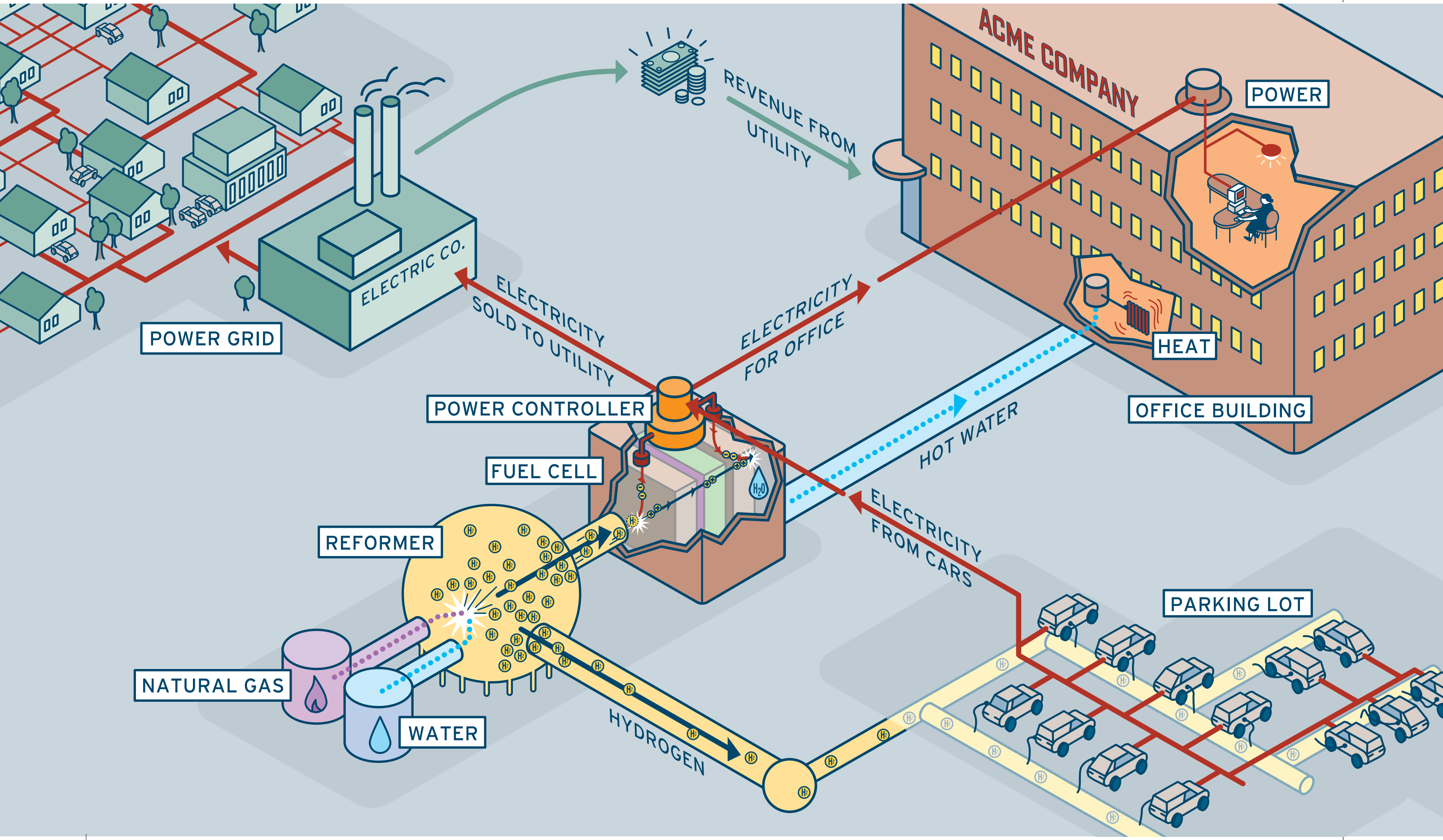
To Lovins, efficiency means living well while reaping the rewards of "negawatts," his term for watts of saved energy. Negawatts lever-

Hydrogen could potentially generate heat and electricity for homes and office buildings, as well as electrical power to drive a new kind of automobile.

age even larger savings upstream in energy production. Typically, it takes three or four units of fuel—coal, oil, or natural gas—to produce one unit of electricity delivered to a customer's home. So the homeowner who adjusts his refrigerator and conserves, say, one kilowatt-hour of electricity might save the equivalent of four kilowatt-hours of fuel at the power plant.

Energy specialist Jonathan Koomey '84, a staff scientist at Lawrence Berkeley National Laboratory currently serving as a senior fellow at RMI and MAP/Ming visiting professor of energy and environment at Stanford, explains that in our current power system, two major losses of energy occur during the journey from natural resource to user. First, about two-thirds of the energy in fossil fuels burned in older steam plants is lost as heat and does no useful work. In newer, combined-cycle plants, which use both steam and gas-turbine generation, this loss totals less than 50 percent. Such combined-cycle plants have monopolized new construction for the past five to 10 years, but still represent less than 20 percent of U.S. generating capacity. Second, there's a 6 to 10 percent loss in the transmission and distribution of electricity from the power plant to the consumer. Overall, then, somewhere between half and three-quarters of the innate energy of the fuel gets lost without turning on a single light. From this comes the power of the negawatt: save one unit of electricity at the point of end use, and a multiplier effect ripples backward to save two to four units of fuel energy at the production end.

At least two states, California and Oregon, actually reward public-distribution utilities for helping consumers make negawatts. ("The other states reward them for selling more power," Lovins notes.) In 1992, for example, California's biggest private utility spent more than $170 million to help consumers save electricity. That generated nearly $400 million in savings—of which 89 percent went to consumers in the form of lower bills, and 11 percent, in the form of higher dividends, to the stockholders, who also avoided the investment risk of building generating capacity. This shared-savings arrangement "added over $40 million to the bottom line in 1992—the second-biggest source of profit that year—at no cost or risk to the company," Lovins explains. "And it changes the culture when you align the incentives of providers and customers."

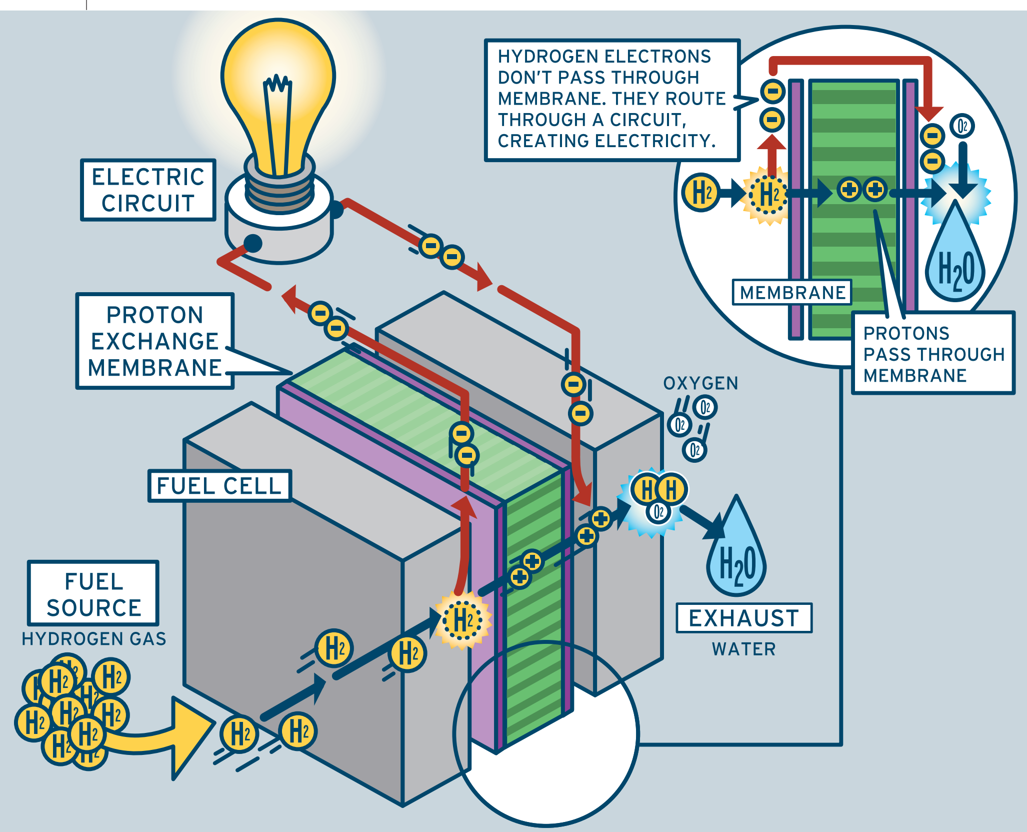


A future hydrogen-powered workplace. Fuel-cell-driven cars "gas up" on hydrogen (in yellow) piped from a natural-gas reformer, and send electricity (in red) back to the power controller outside the workplace. The power controller, running its own much-larger fuel cells, sends electricity and hot water (in blue) to the office building and can sell surplus electricity to the power grid, creating a revenue stream for the company.

Ratchet negawatts up to global-scale economics. During the period from 1977 to 1985, which Lovins calls "the last time we paid attention to oil consumption," the United States improved the average fuel economy of its domestically made new cars by 7.6 miles per gallon. During those eight years, the American economy grew by 27 percent, oil use fell 17 percent, oil imports fell 50 percent, and imports from the Persian Gulf dropped 87 percent. Then the price of oil dropped, the SUV invasion began, and American cars resumed guzzling gas. But "The 1977 to 1985 experience broke OPEC's pricing power for a decade," Lovins asserts. "If we had kept that pace up for one more year, by 1986 we wouldn't have needed a drop of oil from the Gulf. Or if we had resumed doing that in January 2001, by May 2003 we'd have eliminated as much oil as we import from the Gulf."

Now take efficiency a step further, to autos powered by hydrogen fuel cells, which might cruise at 100 miles per gallon, making the U.S. light-vehicle fleet five times as efficient. "We could save eight to 11 million barrels of oil a day," Lovins says. "It would be like finding our own Saudi Arabia under Detroit. And if everyone in the *world* drove fuel-cell cars, it would be the equivalent of a nega-OPEC."

Such an energy revolution would dramatically shift the tectonic plates of international politics and economics. Oil imports would cease to be a factor in American foreign policy. The United States might no longer be the odd man out in international environmental agreements. And Lovins insists that the switch to hydrogen would not strand past energy investments: oil-dependent economies like Mexico and Russia, he says, "will make more money from the hydrogen in oil than from oil itself."



A fuel cell diagrammed. Hydrogen gas pumped past the anode (in gray, at left) hits the proton exchange membrane (green sandwiched in purple coatings) and has its electrons stripped off. These electrons can then be routed through a circuit as electricity (red pathway), powering, for example, a light bulb. The hydrogen's protons pass through the membrane and bond with these electrons and oxygen at the cathode (in gray, at right), forming the fuel cell's "exhaust" product, water.

A less oil-thirsty United States might be a good thing for the world, and also a boon for developing nations, which go heavily into debt to buy oil at prices this country bids up—and because, as Lovins says, "A good predictor of instability in developing counties is the discovery of oil."

So how might we power a post-petroleum world? First, Lovins says, forget about nuclear power. "Nuclear power died of an incurable attack of market forces," he explains. "Not one investor showed up this year at the American Nuclear Society's Nuclear Revival conference. New nuclear energy costs twice as much per delivered kilowatt-hour as wind power, five to 10 times as much as coproducing electricity and heat from natural gas in buildings and factories, three to 30 times as much as electric end-use efficiency. Furthermore, you can't have nuclear power without nuclear proliferation—but even that argument becomes superfluous when you realize it's the most expensive way to make electricity." (And, he adds, electricity is unrelated to the U.S. oil problem: only about 2 percent of our electricity comes from oil, and only 2 to 3 percent of our oil makes electricity, nearly all of which comes from coal, natural gas, water, and nuclear power.)

Wind is another story. By 2002 there were 31 billion watts of wind power operating worldwide, and windpower has been growing by 20 to 30 percent annually. In plains areas, the potential is especially great. "In tribal lands in the Dakotas," says Lovins, "the windpower potential is equal to half of all the U.S. generating capacity." Jonathan Koomey agrees that "wind's potential is pretty large—on the order of our total national electricity use. In Great Britain, it might even be several times national electricity consumption, due to the favorable wind conditions surrounding the British Isles."

Wind, however, is variable. Koomey points out that you can build a megawatt of wind-power capacity, but it might produce only 30 to 35 percent of the time, whereas a traditional power plant can operate 65 to 80 percent of the time, and at any desired hour. But an intermittent energy source like wind can become a steadier, more valuable stream of both energy and revenue if supplemented by load management (letting people choose when they use electricity), hydropower, storage, or hydrogen energy—and renewable sources like wind and solar energy don't pollute or diminish. Furthermore, says Lovins, "The god of energy does not raise the price of sun or wind." Consequently, such power sources avoid the costly financial risk of volatile fuel prices, making them more profitable. With an eye to that upside, General Electric purchased Enron's windpower division after that conglomerate's breakup. The world's largest windmill maker, the Denmark-based Vestas Wind Systems, controls about a third of the market; its share price has increased twentyfold in the past three years. One-fifth of Denmark's electricity comes from wind, and the windpower industry there employs three times as many people as the electric utility industry.

Today, sources like wind and solar power "are expensive," says William Hogan. "With subsidies, it's easy to develop technologies that produce energy expensively." Currently, hydrogen power is costly, too, and its future may depend less on science and engineering than economics. The executive director of fuel-cell activities at General Motors, Byron McCormick, has com-

Graphic by Funnelinc.com

pared building a hydrogen infrastructure in this century to investing in railroads in the nineteenth century or interstate highways in the twentieth. "There'll be a point in time—maybe it's a year or two away," he told the *Wall Street Journal*, "where these kinds of how-do-you-get-it-funded decisions [paying for the infrastructure] will be more important than the technology."

The Soft Path of Hydrogen

Hydrogen makes up three-quarters of the matter in the universe. It's a highly sociable gas, quick to combine with other substances, and hence in nature is never found by itself. Having atomic number one (each hydrogen atom has a nucleus of one proton, with a single electron in orbit), hydrogen is also the lightest element, making it a fugitive substance that disappears by floating away if not by forming compounds. The word hydrogen comes from a Greek word meaning "water former," and of course the most important hydrogen compound for humans is H_2O.

Unlike sun, wind, water, petroleum, and coal, hydrogen is not an energy *source,* but rather an energy *carrier.* An energy carrier is a way of transmitting energy, not creating it. While crude oil is an energy source, gasoline is a carrier—it provides portable mobility fuel. Electricity, which can transmit energy over hundreds of miles, is a pure carrier. (We cannot yet make use of the static electricity in the air—e.g., lightning bolts. In that form, electricity *would* become an energy source.)

Hydrogen is the most concentrated energy carrier in the universe: 2.2 pounds of it can carry the same energy as 6.2 pounds of gasoline. That's a key reason why liquid hydrogen makes excellent rocket fuel. Unlike electricity, hydrogen is easily stored in large amounts as a gas or a (costlier) supercold liquid. Hydrogen doesn't support life, but it is nontoxic. Though it is seldom burned as a plain fuel like coal, hydrogen gas *can* burn, but requires four times the concentration of gasoline fumes to ignite. When it does burn, hydrogen's clear flame produces only heat and water—no choking smoke or soot, which are carbon products. Another safety advantage is that its clear flame cannot sear skin at a distance.

In a sense, we are already two-thirds of the way toward a hydrogen economy, because more than two of three fossil fuel atoms we use today are hydrogen (the rest are carbon). "Hydrogen is actually worth more *without* the carbon attached than it is *with* the carbon," says Lovins. Consequently, converting from a fossil-fuel energy economy to a hydrogen economy, he asserts, "will be profitable for everyone, including the oil companies." Worldwide, we are already making, for industrial use, two-thirds of the hydrogen needed to displace the world's gasoline, he says: "We would only need to expand the hydrogen industry by severalfold if hydrogen were used in state-of-the-art efficient vehicles."

The incentives to do that are not yet in place. "I'd be surprised if the economics of hydrogen were competitive with oil," says William Hogan. "Fuel cells are better today than they were 30 years ago—but oil is cheaper, too. Getting the prices right is the first step; we have many regulatory rules that dictate energy prices. Price things correctly, and we might see more distributed electricity-generating technology [e.g., fuel cells] penetrating the marketplace."

The economic equation begins with capturing the hydrogen itself, which, given its highly reactive nature, means prying it loose from compounds like water and natural gas. Extracting hydrogen from coal or natural gas is called "reforming" these fossil fuels; currently, the United States converts more than 5 percent of its natural gas output into industrial hydrogen; refineries use about half of that in making gasoline and diesel fuel.

Reforming involves mixing natural gas with steam (which produces at least half of the hydrogen in the reaction). The process also releases some carbon dioxide, which Lovins recommends injecting back into the ground where it won't aggravate the greenhouse effect but can re-pressurize oil or gas wells. Some critics claim that reforming hydrogen from hydrocarbons may cause as much environmental trouble as burning fossil fuels, but Lovins says that following the process through to the end product—auto miles traveled—proves otherwise. "[A] good natural-gas reformer making hydrogen for a fuel-cell car releases between 40 and 67 percent less CO_2 per mile than burning hydrocarbon fuel in an otherwise identical gasoline-engine car," he writes, "because the fuel cell is two to three times more efficient than the engine."

Yet if we create hydrogen only by reforming hydrocarbons, many of the problems of a fossil-fuel economy, such as pollution and scarcity, will persist. Lovins sees reforming as a transitional step. Electrolysis—breaking down water into hydrogen and oxygen by passing an electrical current through it—can also create hydrogen. But electrolysis costs more than reforming hydrocarbons, unless a very cheap source of electricity is available, or the hydrogen is a byproduct. Large-scale windpower could probably provide cheap enough electricity, he reckons, and in the Dakotas alone, windpower could make enough hydrogen to fuel, at high efficiency, every highway vehicle in America. There are also experimental processes to make hydrogen using light, plasma, and microorganisms.

At 100 miles per gallon, a U.S. fleet of hydrogen fuel-cell cars "would be like finding our own Saudi Arabia under Detroit," says Lovins.

Since hydrogen is highly reactive, many wonder about the dangers of hydrogen fires or explosions. Though all fuels are hazardous, hydrogen is probably safer than hydrocarbon fuels. By volume, it weighs only 7 percent as much as air; hydrogen is four times as diffusive as natural gas, and 12 times as diffusive as gasoline—so a hydrogen leak rapidly dissipates as the gas rises away from its source.

It's difficult to make a hydrogen-air mix explode. Though the gas does ignite readily—a transient spark can set it off—it will burn, rather than explode, in open air. A few years ago, NASA scientist Addison Bain investigated the 1937 *Hindenburg* disaster and concluded that probably no one aboard the dirigible was killed by a hydrogen fire; the 35 fatalities were people who jumped out, succumbed to burning diesel fuel, or were killed by flammable furnishings or the flaming blimp itself. The clear hydrogen flames swirled harmlessly above the 62 survivors, who rode the burning *Hindenburg* safely to earth.

Fuel-Cell Empowerment

The fuel cell is the crucial technology that converts hydrogen and oxygen into electricity and heat—powering and heating buildings, machinery, *(please turn to page 92)*

(continued from page 35)

and cars, for example. Fuel cells are hardly new. In 1839, British physicist William Grove reasoned that if an electric current could split water into hydrogen and oxygen, the reverse process of combining the two gases might produce electricity and water. He was right.

Like a battery, a fuel cell is a device for converting chemical energy into electrical energy. Both batteries and fuel cells have positive and negative electrodes in contact with an electrolyte—an electrically conductive liquid or gas. But batteries are energy storage devices, and they will stop making electricity when they discharge or their chemical reactants are consumed. Fuel cells, in contrast, can produce electricity as long as they are supplied with fuel. While batteries need to be recharged, fuel cells need to be refueled.

The modern fuel cell takes several forms; one of the most popular is the Proton Exchange Membrane (PEM), currently the lightest and easiest to manufacture. It has two electrodes—an anode (which attracts negative ions) and a cathode (which attracts positive ones)—separated by a thin membrane, typically special polymers dusted with platinum (see diagram, page 34). When a hydrogen molecule (H_2) passes through the membrane from the anode side, its electrons (negative ions) are stripped off and can be routed through a circuit as electricity. The protons (positive ions) pass through the membrane to the cathode, where they bond with oxygen—and recombine with the electrons that have gone through the circuit—to create H_2O in a heat-generating, low-temperature chemical reaction. Thus the fuel cell's output is electricity, heat, water—and nothing else, because there's no combustion.

In the 1960s NASA developed fuel cells for use in rockets and they have powered space missions ever since. Not only do they produce clean and ultra-reliable power, but the astronauts can drink the water. In 1966 General Motors produced a fuel-cell prototype car called the Electrovan that had a driving range of 150 miles. Since then, fuel cells have found a range of uses in buildings and specialized applications.

Fuel cells represent decentralized power—they make electricity on the spot, rather than importing it from distant generators via transformers and long high-tension lines, with sizable losses in transmission. "You want to deploy fuel cells in buildings and vehicles in an integrated fashion," Lovins says, "so each of them makes the other happen faster." Deploying hydrogen-fed fuel-cell cars, however, poses a Catch-22: there is no infrastructure to distribute hydrogen, hence no "gas" stations for fuel-celled cars—but no fleet of hydrogen-powered cars exists, because there isn't an infrastructure to gas them up.

Lovins proposes an ingenious, bottom-up way out of this paradox. There's no need, he says, to build a massive hydrogen distribution network at the outset. (General Motors and Royal Dutch/Shell have proposed building thousands of hydrogen fueling stations at costs estimated from $10 billion to $19 billion; others envision central production and a national pipeline network costing up to $300 billion.) Instead, says Lovins, the transition could work on an "earn as you go" basis, starting with office buildings.

Buildings, he notes, consume two-thirds of the electricity in the United States. Imagine a high-tech operation whose many computers can't afford to go down, and whose standby generators are costly, noisy, and polluting. Unplug this company from the power grid and install instead an on-site natural-gas reformer and a fuel cell to power its headquarters. (There are already more than 100 fuel-cell-powered buildings up and running.) "You could lease hydrogen-ready cars to people who work in or near buildings that have fuel cells," Lovins says. Buildings' power supplies are sized for peak loads that rarely occur; the reformer could easily make more hydrogen than the building actually needs—and could sell off the surplus hydrogen, pumping it into employees' cars while they work inside.

It doesn't end there. Private cars spend 96 percent of their time parked, and while waiting around for the commute home, could

Green Buildings

SINCE 1991, ROCKY MOUNTAIN INSTITUTE has worked with clients like the Pentagon, Oberlin College, the White House, and the 2000 Sydney Olympic Games to forward "environmentally responsible architecture," says William Browning, a founder and principal of RMI's Green Development Services group.

Take, for example, the new Condé Nast Building at 4 Times Square in New York City, which was a pilot LEED building. (LEED is the acronym for Leadership in Energy and Environmental Design, a program of the U.S. Green Building Council—www.usgbc.org—for voluntarily rating structures on variables like energy efficiency, water efficiency, use of recycled materials, and light pollution.) Completed in 2000, the new building consumes 35 to 40 percent less energy

©JEFF GOLDBERG/ESTO

The Condé Nast building in Times Square capitalizes on energy advantages from fuel cells and solar power.

than a standard Manhattan office building. With some consulting help from RMI, the developer, the Durst Organization, removed 40 percent of the mechanical HVAC (heating, ventilation, air conditioning) systems from the design by installing two 200-kilowatt fuel cells and solar cells in the spandrels of some of the upper floors. "HVAC is very expensive," says Amory Lovins. "Usually it's somewhere between 9 and 14 percent of the construction budget." The developer's savings paid for the fuel cells and solar cells.

Because employees are the largest expense of most organizations, green design can greatly enhance profitability by its measurable effect on worker productivity—gains of 6 to 16 percent, or more. Take good old-fashioned daylight. Energy consultant Lisa Heschong studied a retail chain and found a 40 percent increase in sales per square foot of space in daylit stores over electrically lit ones. Heschong measured a 20 to 26 percent improvement on tests taken by students in schools with good, glare-free daylight.

William Browning contrasts such "real buildings" with the standard model for a windowless convention center: a "black box" that takes people out of time, supposedly "so you have their attention." Instead, Browning says, "We find that people want daylight and respond better to daylight. There are subtle variations in color and intensity of light that have a physiological response. When you look out a window at a distant, very different view, the eye relaxes, the lens flattens." He contrasts natural light with the subliminal flickering of certain fluorescent fixtures and computer screens that produce conflicting signals in the eye and can cause eyestrain and headaches. Sick buildings, he says, "are often not a problem of air quality, but lighting."

"Reducing waste, eliminating toxicity, using less water or carbon can be a competitive advantage, not necessarily a burden," says Christina Page, who leads RMI's natural capitalism educational initiatives (www.natcap.org). "A lot of it comes down to designing stuff right the first time: you eliminate the onerous cleanup job down the road. But it can also save money and boost profits right now."

Take the case of Interface, a carpet company that built a new Shanghai factory in 1997. One of its industrial processes called for 14 pumps. The original design sized those pumps at a total of 95 horsepower. But Dutch engineer Jan Schilham cut the pumping power to only 7 horsepower—a 92 percent energy saving. The key was using short, straight, fat pipes instead of the traditional practice: a long, twisting "spaghetti" of skinny pipes. Fat pipes cost more per foot than thin ones, but flow friction drops as nearly the fifth power of a pipe's diameter—so making the pipes 50 percent fatter reduces the friction by 86 percent. And by laying out the pipes *first*, and only then placing the equipment they connect (the reverse of standard practice), Schilham eliminated needless twists and turns—extra bends and length that make the friction in the system three to six times higher than it should be. The 92 percent saving in pumping power allowed Interface to buy smaller pumps and motors, reducing capital cost, speeding construction, and improving long-term performance, as well as saving on energy bills.

COURTESY OF UTC FUEL CELLS

COURTESY OF HDR

Above, left: A green fuel-cell stack powers the New York City Police station in Central Park. Clockwise from above, right: The First National Bank of Omaha's 200,000-square-foot Technology Center boasts modern exterior and interior design and a futuristic power plant of 400-kilowatt fuel cells behind the glass.

run their own fuel cells to make electricity and sell it back to the grid, or to the building itself—recouping much or most of the auto's cost for its owner. "Cars could more than run a building," Lovins asserts. "Each car can send out 25 to 45 kilowatts of electricity—enough to run dozens of typical houses. Cars would bring people to work, and then the garage under the building would pay them to park there. It doesn't take that many people! A national fleet of fuel-cell-powered cars would have six to 12 times as much electrical generating power as the whole American power grid does now. Only a small fraction of that fleet could replace all the coal and nuclear plants." Lovins estimates that eventually, converting fewer than one-third of existing American filling stations would be enough to keep the nation's automobiles running—silently—on hydrogen, and could cost less than $10 billion.

Furthermore, since fuel cells are such a stable, reliable source of electricity, they could answer a major problem of our vulnerable power grid: the inevitable blackouts. During the massive power failure of August 14, 2003, at least one building in New York City had no problems—the police station in Central Park, which makes its own electricity with fuel cells. "They decided that it was cheaper than running power lines in there [to Central Park]," Lovins explains, "and they wanted power that would never go off." Fuel cells also keep the computers humming and the lights on at

COURTESY OF TOYOTA

COURTESY OF HYPERCAR

Toyota's FCHV hydrogen fuel-cell car (above, left) is a prototype based on its Highlander SUV. Hypercar's carbon-fiber mock-up (above) dramatically reduces vehicle weight without sacrificing body strength, potentially helping to boost fuel efficiency by a factor of five.

the First National Bank of Omaha, which has a national credit-card business. In 1999, the bank installed two 400-kilowatt phosphoric-acid fuel cells in the basement of its 200,000-square-foot Technology Center, which requires 300 kilowatts of power. One fuel cell is a back-up, and the local power grid is actually the second back-up. The bank wanted an extremely dependable power source (their systems designer claims—and guarantees—99.9999999 percent reliability) because having their computers go down could cost as much as $6 million per hour in lost business.

Fuel cells could also strengthen homeland security by decentralizing the generation of power. Centralized power plants pumping electricity downstream to customers at great distances not only waste power in transmission, but are highly vulnerable to terrorist attack. A decentralized system, with smaller amounts of electricity generated close to the point of use, would be far more secure. And fuel-cell technology might also help the military. The 70-ton M-1 Abrams tanks, which get 0.56 miles to a gallon, "can't go fast because their fuel supply can't keep up with them," Lovins says. "The move to hydrogen may be accelerated by the military's interest in ultralight tactical vehicles."

Light, Fast, Strong, and Silent

Between 100 and 300 fuel-cell-powered cars are on the road today, but these are prototypes and experimental cars, far too costly for the consumer market. (Toyota and Honda have leased a few prototypes in California for $10,000 a month.) "It's not easy to make a good fuel cell. But it's easier than making a good battery, " Lovins stated in his Given Institute talk. "From then on, it's mass production."

Lovins has a way of dismissing a vast array of technical and market obstacles with remarks like, "From then on, it's mass production"—and some energy analysts feel that he underestimates the difficulties involved. "Many of the things Amory has said have been insightful and perceptive," says the Kennedy School's Hogan. "But I would never invest my own money in any of his schemes."

Yet the fuel-cell car, if viable, does promise some impressive advantages. The great efficiency that such a car delivers does not occur between the wellhead and the fuel tank, but between the tank and the wheels. Because the power train of an internal-combustion car dissipates 85 percent of the fuel's energy before it reaches the wheels, more efficient technology can easily produce large gains in mileage. "The fuel cell propels the car two to three times as efficiently as a gasoline engine," Lovins declares. "It's a fallacy to compare hydrogen to other fuels in terms of cost per unit of *energy*. You want to look at cost per unit of *service*—how many miles can you drive?" Lovins cites "widely accepted numbers" that peg the fuel costs of driving gasoline-fed autos at five cents per mile and reformed-hydrogen cars at 2.5 to 3.5 cents per mile.

Prototype fuel-cell cars run almost silently. They are quiet because a fundamentally different mechanism propels them. There is no internal combustion engine, and so firing pistons, revving engines, and the lurching acceleration from shifting gears go away. Instead, the fuel cell drives an electric motor that turns the wheels—it's a far simpler vehicle, lacking spark plugs, engine oil, and a transmission. Yet it moves with alacrity. The Toyota prototype can accelerate faster than a six-cylinder gasoline car of the same model, and drive at up to 96 miles per hour (the motor could go even faster, but its computer was programmed for that upper limit). Its only emission is water—perhaps 2.5 gallons per 100 miles, sprinkled harmlessly onto the pavement.

It also has a range of 186 miles—and there's the rub. Drivers generally want to travel at least 300 to 400 miles on a tank of gas—in this case, hydrogen gas. Current prototype cars store hydrogen in carbon-fiber tanks compressed to 5,000 pounds per square inch, but cannot store enough of it to support long-distance travel. Supercooled liquid hydrogen is far more dense, but the process of liquefying the gas, and keeping it cold, is itself costly and energy-intensive. Lovins notes, however, that newer tanks can safely operate at 10,000 pounds per square inch and have been tested at more than 20,000. Germany has legally approved such aerospace-style tanks, and GM has used them in prototype cars. Taking another approach, some researchers are seeking a new way to store the gas, perhaps in hydrides—compounds that contain hydrogen—that might release the gas gradually and then be "recharged."

Another obstacle is the high cost of fuel cells, no problem for NASA but a severe hurdle to the commuter. It is hard to estimate the true market cost of an item that is still years away from mass production, but some estimates price a fuel-cell stack that could run an automobile at more than $100,000. The PEM fuel cell, favored for light-duty vehicles, typically has that platinum-dusted membrane; one research task is finding ways to build effective fuel cells without precious metals.

Lovins favors another approach. It is to reduce the weight of the car, which allows one to downsize its power plant, solving the storage, range, and cost problems simultaneously. Look what Jaguar did with a conventional car by changing the car's "body in white"—its bare structural core—from steel to aluminum, saving 450 pounds of weight. "That increased fuel economy," says David Dwight, director of business development for Hypercar (www.hypercar.com), a for-profit company in Basalt, Colorado, that RMI spun off in 1999. "The medium-size Jaguar X-6 model had a V-8 engine. They were able to use a V-6 instead, which costs less. All the performance numbers are the same, but it uses less fuel."

Formula I racing limits engine size to three liters, so the way to improve racecar performance is to lower the car's weight: speed and acceleration are a function of power divided by weight. In Formula I racing—where price is no object, but safety is important—cars are made of advanced carbon-fiber materials, which are very strong *and* very light. On the wall of one room at Hypercar is a quotation from Trevor M. Creed, senior vice president for design at Daimler-Chrysler: "If money were no object, you'd make cars out of carbon fiber—we know how. But the cost is prohibitive."

Today, carbon fiber shows up mostly in low-volume specialty applications—jet fighters, tennis racquets, racing sailboats. The key mission of Hypercar is to make carbon-fiber construction affordable for the consumer-auto market. The firm has patented a processing technology for carbon-composite structures that promises significantly reduced costs. The light, strong, carbon-fiber body could greatly improve gas mileage in conventional cars, and would help make a hydrogen car viable by downsizing its power plant by two-thirds. As a bonus, carbon-fiber car bodies are far stronger than steel ones. "Carbon-fiber composites are the greatest crash-absorbing material known," says Dwight.

The Hypercar office has a mock-up of a mid-sized, sleek, German-silver concept SUV designed around the firm's Fiberforge™ manufacturing process for carbon-fiber auto bodies. According to Hypercar's computer simulations, such an SUV with a hydrogen fuel cell installed could get mileage equivalent to 99 miles per gallon and drive 330 miles on just 7.5 pounds of hydrogen. This is the ultra-light, ultra-strong car that, Lovins says, could sell at a competitive price and create a domestic Saudi Arabia. "Think nega-missions in the Gulf," he adds. "Mission Unnecessary."

That is the vision of what smart design—including *policy* design—could bring: clean, efficient, abundant, renewable power. Safe, secure electricity and heat, produced locally in the offices, homes, and cars of America. A United States that supplies its own energy needs, no longer gobbling up the fossil fuels of the world. In fact, a *world* of self-sufficient nations, powering themselves in that same local, small-scale, decentralized way: a billion points of light.

Whether this utopia can be realized will depend on choices made on many levels, from personal consumption to national policy. Lovins's team aims to explicate these choices this spring in *Out of the Oil Box,* a study showing how to get the United States off oil attractively and profitably, even for the oil companies. Controversy is certain, and no doubt critics, academic and otherwise, will have their reasons—perhaps sound ones—why a hydrogen economy cannot work.

But this is nothing new for Lovins; from the beginning, he has heard his ideas called impractical and unreasonable. That doesn't seem to bother him. As a young man working for Friends of the Earth, he once suggested to David Brower that maybe it was unreasonable to expect their kind of lobbying, or the environmental movement, to overcome social and political delays soon enough. "But Amory," Brower retorted, "*reasonable* people have never done *anything.*"

Craig A. Lambert '69, Ph.D. '78, is deputy editor of this magazine.