ENERGY SOLUTIONS FOR A SUSTAINABLE WORLD

SCIENTIFIC AMERICAN

SPECIAL ISSUE

SEPTEMBER 2006
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How to Power the Economy and Still Fight Global Warming

Energy's Future Beyond Carbon

- Cleaning up Coal
- The Nuclear Option
- Hopes for Hydrogen
- Biofuels and Renewables
- Fusion and Other Dreams

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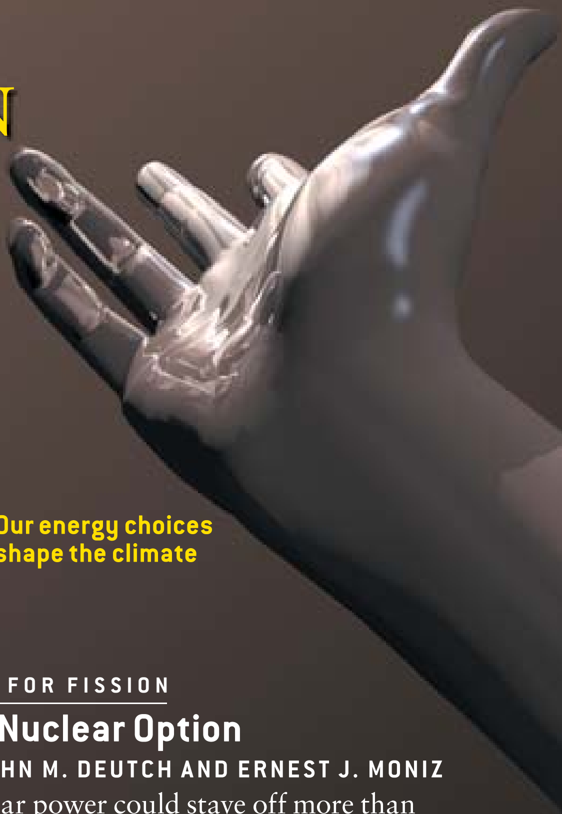
ENERGY'S FUTURE: BEYOND CARBON



Our energy choices shape the climate

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departments

columns

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SA Perspectives

Cooling Our Heels

From Christmas Day in 1991, when the white, blue and red Russian flag rose over the Kremlin, symbolizing the end of the Soviet Union, the U.S. assumed a dominant presence in world affairs the likes of which has not been witnessed since the *Imperium Romanum*. Yet the nation that endorsed the idea of preemptive military action has acted with remarkable passivity when it comes to an energy policy that deals with climate change.

DARK SHADOW: U.S. leadership void impairs progress on climate change.

In a recent scholarly article, economist Jeffrey D. Sachs and geophysicist Klaus S. Lackner of Columbia University noted that the Bush administration's impulse on global warming has been to wait for "something to turn up"—say, the discovery of a plentiful, noncarbon fuel or a technique to eliminate greenhouse emissions at low cost. Global warming has never been the priority it should be.

The reasons are not hard to fathom. People worry that the consumerist way of life that Americans have come to accept as a birthright will have to be scaled back. After all, on average, each U.S. citizen has more than twice the energy consumption of a western European, according to statistics for 2003, and almost 10 times that of a Chinese. To narrow this gap, the U.S. will have to alter its energy-intensive habits. But that doesn't mean we must all live in cardboard boxes. In every plan to tackle warming, Americans will still be better off in 2050 than they are today.

Both technical and policy farsightedness will be needed to achieve the concurrent objectives of growth and sustainability. Decades may pass before hydrogen-powered trucks and cars relegate gasoline- and diesel-fueled vehicles to antique auto shows. In the interim, conservation and better efficiencies in both transportation and electricity generation and usage will allow us to muddle through. Yet for even that to happen, the world's leading economy—and emitter of almost one quarter of human-generated carbon emissions—will have to assume the leadership role that it has so far largely shirked.

Regaining a modicum of credibility will itself prove an immense undertaking. Both the president and Congress need to endorse the ever expanding body of evidence that points to the reality of warming and listen to, rather than harass, scientists who arrive bearing bad news.

Funding for energy research must be accorded the privileged status usually reserved for health care and defense. Yet rhetoric needs to go beyond the mantra that before taking action, more research is needed to eliminate uncertainties surrounding climate science. A ceiling on greenhouse emissions should be set, and then the market should decide how to achieve that target through sales and purchases of emissions allowances. Other measures that must be adopted include stiffened fuel economy standards, carbon taxes and requirements that the largest producers of greenhouse gases report their emissions publicly.

The U.S. should lead by example. An aggressive domestic program would enable this country to influence China, India and other fast-growing developing nations to control emissions. Without the U.S. at the head of the table, the prospects for any meaningful action on a global scale will gradually recede along with the Arctic glaciers.

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Ancient Shell Beads Could Be First Sign of Modern Culture

Three beadlike shells from ancient Israel and Algeria suggest that humans were engaging in symbolic behavior at least 100,000 years ago—25,000 years earlier than previously thought.

Brazilian Trees May Harbor Millions of Unidentified Species of Bacteria

The Atlantic forest of Brazil, which in the past 400 years has been reduced to less than 8 percent of its original size, could contain as many as 13 million unidentified species of bacteria, a new study has found.

Flaws in Placenta May Be Early Sign of Autism

The earliest indicator yet of autism may be the presence of flawed cells in the placenta, scientists say. The findings could lead to earlier diagnosis of the developmental disorder.

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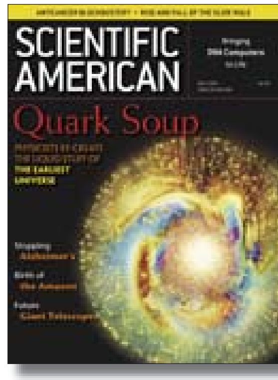

THE MAY ISSUE underscored the maxim that scientific research typically raises more questions than it answers. For instance, in the cover story "The First Few Microseconds," Michael Riordan and William A. Zajc described collider experiments that slammed gold nuclei together at nearly light-speed to replicate the quark-gluon plasma that existed only in the microseconds-old universe. Pondering the mysteries of those microseconds, readers sent some mind-bending questions.

The biggest mail magnet was "When Slide Rules Ruled," by Cliff Stoll, which brought responses, silly and serious, as well as nostalgic recollections from those who lived and ciphered in the primitive times before electronic calculators. Kevin Dixon-Jackson of Macclesfield, England, observed: "As a user of both a Faber-Castell 2/83N and a Hewlett-Packard HP-35, I believe that the slide rule wasted less lab time, because, unlike a calculator, there was no display to turn upside down to show 'funny' words, nor could you play 'get all the integers using only the top three rows of buttons.' Also, it was a straightedge, a T-square and a reach-extender for flicking distant switches and manipulating live electrical wires!"

STICKING IT TO CALCULATORS

In "When Slide Rules Ruled," Cliff Stoll mentioned that it took a 19-year-old French artillery lieutenant to popularize the slide rule. He went on to say that it now "serves as an icon of computational obsolescence." Well, I—a 24-year-old artillery lieutenant—would like to inform you that the slide rule is alive and well in the artillery community in the form of the graphical firing table. Despite having $40,000 fire-direction computers to calculate data, we still use our trusty "sticks" to double-check the solutions. And should our high technology fail, we retain the ability to deliver accurate and timely fire support, all thanks to a few dollars' worth of wood and plastic. Instead of multiplication and logarithms, our sticks have functions like quadrant elevation and time-fuze setting, but the mechanics are the same as those two generations ago. I'm happy we can do our part to keep a little piece of scientific history out of the museum and in the field.

1st Lt. Christopher Lusto, USMC
Fire Direction Officer
Battery G, 2nd Battalion, 11th Marines
Regimental Combat Team 5
Camp Fallujah, Iraq

Stoll did not mention one of the radical effects of replacing slipsticks with calculators: all the answers in engineering and science textbooks needed correction or revision. Their authors, usually professors, had commonly given the problems to a group of their better students to solve.

The consensus answer (ideally) or the median was taken to be correct. The slipstick's solutions of three places with rounding errors could not stand against calculators' eight-place displays, let alone 12-place readouts of 13-place computations. Indeed, current scientific calculators are more precise than the available data.

David F. Siemens, Jr.
Mesa, Ariz.

QUARKY QUERIES

In "The First Few Microseconds," Michael Riordan and William A. Zajc explain what happened in the first 10 microseconds after the big bang. The article also shows a timeline of the universe's history from its birth to 380,000 years after. According to relativity theory, mass and energy create gravity, and time passes slower in stronger gravity fields. Also, in the first moments after the big bang, the matter and energy density of the universe was ultrahigh. If so, the gravity field must have been very strong, and time must have passed very slowly. My ques-

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tion: Are the first 10 microseconds after the big bang equal to 10 microseconds today? Is the big bang's timeline the same time duration as in today's universe?

Fuat Bahadir
Omaha, Neb.

Riordan and Zajc claim that colliders can replicate the conditions of the early universe. Might such a claim be premature, or at least overly broad, because cosmologists now believe that most of the matter in the universe is "dark matter" of unknown composition? Could the infant universe have consisted primarily of precursors to exotic types of matter that we do not understand, or do most physicists believe that the dark matter arose from particles accounted for in the current theory of the big bang?

Ronald Hodges
Palo Alto, Calif.

RIORDAN AND ZAJC REPLY: Bahadir is correct—gravity can affect the passage of time relative to an observer who is distant from the strong gravitational field. That was not the case in the early universe, where there were no observers far removed from the source of gravity, the very dense matter that uniformly filled the entire universe. Perhaps the best way to answer the question is this: if some hypothetical timekeeper could survive both within the fantastically hot and dense quark-gluon matter of the early universe and within the present, the 10 microseconds her clock registered in the first moments of time would be identical to the 10 microseconds measured today.

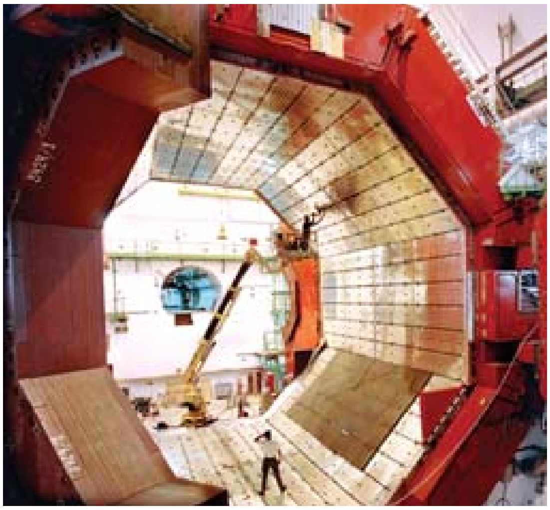
To answer Hodges's question, colliders with enough energy might be able to produce some of the dark matter particles now believed to contribute most of the matter in the universe. When the Large Hadron Collider starts operations next year at the European laboratory CERN, physicists there will search for "supersymmetric" particles predicted by certain theories. The lightest of these is the leading candidate for the mysterious dark matter. Supersymmetric particles are thought to be too heavy to be created in significant quantities at the energies of the Relativistic Heavy Ion Collider (RHIC). The infant universe could indeed have consisted of precursors to such exotic types of matter, which we do not completely understand today.

POLITICAL SCIENCE

The Bush administration has to learn that science is different. At first blush, the suppression of scientific voices outlined by Paul Raeburn in "Legislating Integrity" [News Scan] seems like just another case of the administration ignoring expert opinion when it conflicts with policy; they know the answers they want and will ignore contrary evidence or judgment.

But scientific opinions are different. Elected officials and their appointees have the right to decide policy, but scientific opinions are a matter of information. Let government researchers report what they find, even if it isn't what the White House wants to hear.

Frank Palmer
Chicago



BANG-UP RESEARCH: ALICE detector slated to operate at CERN in 2008 will analyze lead nuclei collisions occurring at about 50 times the energy of RHIC's mini big bangs.

PETER GINTER

Regarding "Legislating Integrity" and the accompanying sidebar, "Arm Twisting?": When a Democratic administration comes to power, will you be as diligent in exposing examples of the suppression of scientific opinion that is skeptical of the human contribution to global warming? I doubt it.

John H. Howe
Fulton, N.Y.

HELP YOURSELF

Michael Shermer's column "SHAM Scam" [Skeptic] about self-help books quotes extensively from Steve Salerno's book *SHAM: How the Self-Help Movement Made America Helpless*. That book does not pass muster as a serious, well-reasoned critique of the self-help industry. The tone is vitriolic, and the arguments are often based on faulty logic. There are ample critiques of the book available out there. The fundamental argument of *SHAM*, and the impulse to write it, seems to spring from the question: "If self-help books work, why do people have to buy them over and over again?" It is a very weak, simple-minded objection, and it does not justify labeling an entire industry insincere or deluded or evil. Replace "self-help books" with "insulin" or "church services" or even "cookbooks," and you'll see the point.

As Dr. Samuel Johnson said, "People need to be reminded more often than they need to be instructed."

Name withheld
via e-mail

CLARIFICATION "Eyeing Redness," by Charles Q. Choi [News Scan], stated that two of the three kinds of color photoreceptors in humans and primates are most sensitive to 550-nanometer-wavelength light, which optimizes them for detecting subtle changes in skin tone from varying concentrations of oxygenated hemoglobin. It should have noted that 550-nanometer light is green-yellow and that skin is greenish-blue when underlying veins contain deoxygenated blood; if there is a high concentration of oxygenated blood, it is reddish-blue.

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50, 100 & 150 Years Ago

FROM *SCIENTIFIC AMERICAN*

Past and Future Universe ▪ Criminal Wit ▪ From Mite to Man

SEPTEMBER 1956

EVOLUTIONARY UNIVERSE—"We have reviewed the questions that dominated the thinking of cosmologists during the first half of this century: the conception of a four-dimensional space-time continuum, of curved space, of an expanding universe and of a cosmos which is either finite or infinite. Now we must consider the major present issue in cosmology: Is the universe in truth evolving, or is it in a steady state of equilibrium that has always existed and will go on through eternity? Most cosmologists take the evolutionary view. —George Gamow"

STEADY-STATE UNIVERSE—"The theory of a steady-state universe leads to many startling conclusions: that the universe had no beginning and will have no end, that space as well as time is infinite, that matter is continually being created throughout space—to mention a few. Human nature being what it is, there has been a tendency to become involved in emotional attitudes toward these concepts, instead of confining the discussion to purely scientific criteria. If the writer, along with critics, has transgressed in this respect, he promises to give some redress in this article. The steady-state theory holds that the large-scale features of the universe do not change with time. Only the galaxies and clusters of galaxies change. —Fred Hoyle"

SEPTEMBER 1906

SCOTT OF ANTARCTICA—"Great Britain may well be satisfied with the information collected in the Antarctic by Capt. Robert F. Scott and his gallant companions. And what did Capt. Scott find after his memorable struggle up the glacier through the mountains? An enormous plateau at an elevation of about 9,000 feet, nearly level, smooth, and featureless, over which he traveled directly inland for over 200 miles, seeing no sign at his furthest point of any termination or alteration in character."

SMUGGLERS' INGENUITY—"Alcohol without a doubt is the article most often smuggled through the gates of Paris. A single man can carry quite a quantity of alcohol, and in quite a different sense from that usually applied to drunkards. A smartly-dressed gentleman, under his spotless waistcoat and white shirt, carries an India-rubber plastron brimful of alcohol. True, his appearance is rather bulky, but then he can probably put that down to good living. I have known even an immaculate-looking tall hat to contain heavily taxed liquor. —By an officer of the Paris Customs House"

WELL-HEELED SMUGGLER
hides alcohol in his top hat, 1906

SEPTEMBER 1856

BEFORE *ORIGIN*—"Lorenz Oken and the author of 'Vestiges of Creation' have endeavored to prove that the different races of animals now existing are developments, not separate creations, and that life on our earth through myriads of ages gradually improved—developed—into its present diversified expanded perfections. Hugh Miller completely exploded this theory, so far as it related to *all* life commencing at a *point,* and developing upwards. Still, he admits, in his 'Footsteps of the Creator,' that successive creations of races exhibit developments, and so does Louis Agassiz, and thus they grant half the argument, at least, to those who believe in the gradual development of life from a mite up to a man."

GUANO MIRAGE—"Some time ago it was announced that a guano island, not laid down in any map, had been discovered by one of our merchant ships in the Pacific Ocean. The U.S. sloop-of-war *Independence* was ordered to take a peep at the Islands. Captain Mervien reports: 'Intense interest appeared to pervade all minds, fore and aft, as the ship neared the promised El Dorado of the mercantile and agricultural interests of our country. The delusion, however, was but transitory; a nearer view revealed to our astonished vision the whole islands covered with a deep green mantle of luxuriant vegetation, indicative certainly of the strength of the soil and heavy rains common in this locality, as also of the worthlessness of the deposit thereon as an article of commerce.'"

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FORENSICS

Missing No Longer

INTERNATIONAL COMMISSION FORGES AHEAD TO IDENTIFY GENOCIDE VICTIMS **BY SALLY LEHRMAN**

Tuzla, Bosnia-Herzegovina—Forensic anthropologist Cheryl Katzmarzyk stands above three metal tables pushed together, hundreds of finger bones laid out neatly before her. Not long ago the metacarpals had been found dumped together in a mass grave, the jumbled remains of bodies dug up and moved several times in an effort to conceal a massacre. "There are about 22 people here," she estimates—bits and pieces of the roughly 8,000 Bosniak men and boys killed in Srebrenica alone.

For 10 years, the International Commission on Missing Persons (ICMP) has been assembling data on the 40,000 civilians who disappeared in the wars that followed the breakup of the former Yugoslavia. Its archaeologists help to locate burial sites and assist in exhumation. Then Katzmarzyk and other forensic anthropologists work with molecular biologists to apply state-of-the-art techniques to reassociate and identify remains. It is a daunting assignment: The bodies, mostly men of about the same age, have been buried for years. Decomposing pieces of one person could be spread into five different graves and commingled with other parts.

EXHUMATION begins the DNA forensic process. Officials from the International Commission on Missing Persons, including Queen Noor of Jordan (*fourth from left*), oversee this June 2003 disinterment of a mass grave outside Sarajevo.

AMEL EMRIC *AP Photo*

The quest to identify victims began in 1992, when the United Nations asked forensic adviser William Haglund and a team from Physicians for Human Rights to investigate a mass grave in Croatia. Four years later they returned to document war crimes in the Srebrenica region and collect data to match missing people with exhumed bodies there. Early on, families resisted, insisting their relatives were alive, Haglund recalls. The investigators had to build trust and, before asking for a blood sample, have a potential identity in hand. But that led to delays in collecting DNA for shipment overseas and lots of mistaken probable identifications. In massacre situations, up to 40 percent of circumstantial matches turn out to be wrong, according to one recent study in Kosovo.

Furthermore, the original investigation's primary purpose was prosecution, not identification. The G7 Summit nations voted in 1996 to fund an international laboratory

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MATCHING THE MISSING

Nationalistic conflicts and "ethnic cleansing" during the 1990s left tens of thousands in mass graves all over the former Yugoslavia—primarily in Bosnia-Herzegovina, Kosovo, Serbia and Croatia. The International Commission on Missing Persons asks those who have a missing relative to donate blood samples for potential DNA matches. Two or more relatives must provide their DNA before a precise identification is possible. Reported matches must achieve a minimum 99.95 percent certainty.

- **Estimated total of missing people: 40,000**
- **Blood samples donated: 80,805**
- **Missing relatives of donors: 27,291**
- **Bone samples successfully analyzed: 18,856**
- **Unique DNA profiles from bones: 14,165**
- **Number of matches between an individual's remains and living relatives: 10,025**

Data as of July 12

that would focus on the missing and could analyze DNA on-site. Many were skeptical, though, that the newly formed ICMP would succeed. "This was based on a sincere concern that the DNA-identification program could create expectations on the part of families and would be unable to deliver," recalls Eric Stover, who directs the Human Rights Center at the University of California, Berkeley, and was on the forensic team in Croatia. Now, he says, the ICMP's work has become a blueprint for similar efforts elsewhere.

Progress was indeed slow until six years ago, when the ICMP shifted to blind DNA matching. Now, instead of starting with family interviews and anthropological forensics, scientists begin with genetic analysis of the remains. Technicians painstakingly recover whatever DNA they can from a bone, then compare 16 markers against a database of DNA profiles from 80,000 survivors who lost a family member during the war. "We're now at our highest efficiency ever," says ICMP forensics director Tom Parsons. In early July, just after its 10th anniversary, the ICMP identified its 10,000th person. Parsons expects results to soon reach 5,000 a year.

To piece together the bodies from Srebrenica, Katzmarzyk first conducts bone-to-bone DNA matches, relying on just six markers. Working with a team of interns and local experts, she next reassembles as much of a skeleton as possible. Team members check bones for consistency in length and robustness and make sure that anomalies such as rheumatoid arthritis show up in both knees, not just one. They estimate age and stature based on known standards of bone growth and degeneration specific to the Bosniak population. Then a bone sample goes out for genetic matching with the family database. Without DNA, muses forensic anthropologist Laura Yazedjian as she contemplates one reassembled skeleton, "this guy would have been without a name forever." Finally, the team cross-checks age and stature and asks relatives if they recognize clothing. A court-appointed pathologist goes through the entire package with the family, who must agree to declare the person dead.

The political situation is far from settled in Bosnia-Herzegovina, and ethnic and nationalistic tensions still simmer. Parsons worries that international interest could fizzle before the job is done, even though he believes tracking down the missing is central to societal reconstruction. Not only does it allow families to know the truth at last, but it brings everyone face-to-face with concrete statistics. In Srebrenica some still insist that only 2,300 died in a fair military battle. But the evidence from graves tells a different story. As Parsons puts it: "We have gone from people who were being driven to extinction and crammed into the earth 10 years ago, to [families] being given their rights back, their homes back, their legal status back." DNA forensics is restoring humanity not just to the dead, it appears, but to the living as well.

Sally Lehrman is based in the San Francisco Bay Area.

APPLIED PHYSICS

The Next Generation

NEW SUPERCONDUCTING WIRES COME CLOSER TO MARKET BY GRAHAM P. COLLINS

The 1987 discovery of materials that conduct electricity perfectly at temperatures above the boiling point of nitrogen (–196 degrees Celsius) seemed to herald a revolutionary era of technology. But turning the promise of these so-called high-temperature superconductors into commercial reality has proved to be a long, arduous task. It is one thing to produce a small sample of a superconductor for experiments in a laboratory and quite another to manufacture hundreds of meters of high-quality wire for applications. Until recently, the leading commercial high-temperature superconductor technology involved wires made of the elements bismuth, strontium, calcium, copper and oxygen (BSCCO). Now a second generation of wires, composed of yttrium,

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barium, copper and oxygen (YBCO), looks set to dominate the marketplace.

BSCCO wires are typically made by putting a powder inside a tube of silver that is then heated and drawn out. But that technique has two significant downsides. First, the cost of the silver makes the wires expensive. Second, manufacturers have little ability to control the detailed structure of the BSCCO cores to optimize the superconductor's performance.

YBCO had other problems that early on left BSCCO in the driver's seat. The chief approach to YBCO wire making is deposition of the material onto a substrate to form a thin ribbon. YBCO, however, tends to form innumerable tiny crystal grains, and if these are not closely aligned, resistance builds up because of the jumps a current has to take from grain to grain. Yet interest in YBCO remained high because well-aligned samples stay superconducting in stronger magnetic fields than BSCCO can withstand; many applications, such as magnets and motors, require that the wires function in such fields.

Over the past decade, researchers have largely solved the crystal grain problem by depositing a layer of a material such as cerium oxide on the substrate before laying down the YBCO. The cerium oxide serves to help align the YBCO grains. Researchers, primarily at Los Alamos National Laboratory and Oak Ridge National Laboratory, have developed two wire-making technologies incorporating the grain-aligning layer. The approaches, which go by the acronyms IBAD (which uses ion beams to help align the crystals) and RABiTS (which relies on rollers and heat to prepare the substrate), have been taken up by wire-producing companies.

Much remains, however, to further improve the wires' performance. For example, although YBCO's resilience to magnetic fields exceeds that of BSCCO, even greater performance is needed for higher-field applications. In 2004 Stephen Foltyn's group at Los Alamos showed that introducing nanoparticles of barium zirconate greatly improved YBCO's magnetic characteristics. Amit Goyal and his colleagues at Oak Ridge reported similar work earlier this year.

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SUMITOMO ELECTRIC INDUSTRIES

POWER CABLE made of superconducting wire (*silvery ribbons*) is being used in a high-voltage demonstration project in Albany, N.Y.

The promise of second-generation wires is so great that wire-producing companies such as American Superconductor and SuperPower have switched to producing YBCO tape in place of the older BSCCO wires. Both companies expect to deliver around 10 kilometers to customers in the coming year. By the end of 2006 SuperPower aims to have the manufacturing capacity to produce a million meters of the wire annually.

The wire comes in pieces each 100 to 300 meters long, but the companies are working on increasing that length and proudly announce when they achieve a new world-record combination of YBCO wire length and current-carrying capacity. SuperPower is now routinely producing lengths greater than 300 meters and holds the record for YBCO with a 322-meter wire.

Customers are developing devices using the second-generation wire for a variety of applications, including motors, generators, cables and transformers. The first major demonstration project involving YBCO wire will be a high-voltage cable running between two power substations in Albany, N.Y. Most of the 350-meter cable is made of BSCCO wire, but a 30-meter segment will be replaced with YBCO cable. Building that 30-meter length of cable will use up around 10 kilometers of YBCO tape. Installation and commissioning of the second-generation wire are scheduled for June 2007.

A SUPERCONDUCTING SANDWICH

Superconducting wires made of YBCO come in the form of thin ribbons with the crucial YBCO layer no more than about 1.5 microns thick. If more YBCO is added, the current-carrying capacity of the tape does not increase significantly.

In 2004 Stephen Foltyn and his colleagues at Los Alamos National Laboratory demonstrated a wire made with layers of cerium oxide (which helps to align the YBCO crystals) interleaved with six 0.6-micron layers of YBCO. The multilayered sandwich carried currents up to 1,400 amperes per centimeter width, a YBCO record that still stands.

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BIOTECH

Old MacDonald's Pharm

FIRST DRUG FROM TRANSGENIC GOATS NEARS APPROVAL BY CHARLES Q. CHOI

In the milk of 30 genetically modified goats on GTC Biotherapeutics's farm in Charlton, Mass., is a drug that can literally make your blood flow—the human protein antithrombin, which inhibits clotting. In a dramatic reversal, after European regulators rejected this drug (called ATryn), they now look ready to approve it later this year. The ruling would make ATryn the first human protein made by a transgenic animal for commercial production.

TRANSGENIC GOATS made by GTC Biotherapeutics are ready to create a clot-inhibiting compound called ATryn for sale on the European market.

Perhaps more important, the judgment in favor of the goats paves the way for more drug-making transgenic farm animals. Origen Therapeutics in Burlingame, Calif., has developed a versatile, cost-effective method for genetically transforming chickens—one that is on par with creating transgenic mice, now common in the lab. In principle, the birds could produce a variety of different proteins in their eggs, including drugs.

Traditionally, the biotechnology industry has most commonly relied on mammalian cells grown in vats to generate protein drugs. A number of molecules, including proteins normally found in blood plasma, are hard to produce with these methods. Squeezing large amounts of drug from these cells is difficult as well, driving up their price. The capital costs for a mammalian cell fermentation system that generates 100 kilograms of drug a year reach hundreds of millions of dollars.

On the other hand, 150 of GTC's goats or 5,000 of Origen's chickens could produce roughly the same amount of drug and cost only tens of millions. A transgenic farm's operating costs would also be far cheaper, "at literally chicken feed with our chickens," says Origen Therapeutics's president and CEO Robert Kay.

GTC spent roughly 15 years developing the goats. When the firm was ready in January 2004, it turned to Europe, where the European Medicines Evaluation Agency (EMEA) had guidelines for drugmakers seeking approval to treat patients with hereditary antithrombin deficiency (at the time the U.S. Food and Drug Administration had no comparable approval procedures). Afflicted individuals might suffer problems from clots during high-risk procedures such as surgery and childbirth. The disease is rare, occurring in one in 3,000 to 5,000 people, so few cases are available for study.

This past February an EMEA committee rejected ATryn, considering the five surgical cases that GTC offered insufficient. GTC appealed the decision even though the odds seemed slim. "The number of times companies have successfully appealed a decision against them from a regulatory agency are very few," remarks Philip Nadeau, biotechnology analyst at investment banking and research firm Cowen and Company. On June 1, after bringing in leading European blood specialists and reviewing the findings, the EMEA committee decided to accept data on nine childbirth patients they had excluded initially and "concluded that the benefits of ATryn outweigh its risks." Final authorization on ATryn for use in surgery is expected from the European Commission in September.

The market for patients with hereditary antithrombin deficiency is only about $50 million in Europe and the U.S. combined. ATryn, however, could also find therapeutic uses for burns, coronary artery bypass surgery, sepsis and bone marrow transplants, for up to a $700-million market worldwide.

GTC plans to enroll patients in a hereditary antithrombin deficiency study for the FDA by the end of the year, says Geoffrey Cox, GTC's chairman, president and CEO. Kay hopes the company's success will "lower the general reluctance to take on any new technology" and predicts "we'll see transgenic animals becoming a commonplace manufacturing alternative." Nadeau agrees: "It won't take as long for the second and third transgenic drug to make it to the market as the first."

Charles Q. Choi is a frequent contributor.

POULTRY PRESCRIPTION

Origen Therapeutics in Burlingame, Calif., and researchers at the University of California, Davis, developed a technique reported in the June 8 *Nature* that generates transgenic chickens by inserting genes into germ cells using electrical fields to open pores in the cells' membranes. After these modified cells are injected into normal chickens, they create transgenic progeny. Efforts to make drugs in eggs using retroviruses to carry genes into chicken embryos go back 20 years, notes Origen president and CEO Robert Kay.

This new technique can insert genetic sequences roughly 20 times as long as those possible with viruses, he explains, to help create more complex, larger protein drugs; moreover, it can create a greater abundance of the protein in desired tissues.

EMILY HARRISON

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AEROSPACE

Mach 3 Hunter-Killer

AN ADVANCED TURBINE DESIGN FOR VERSATILE MISSILES **BY STEVEN ASHLEY**

Suppose that U.S. intelligence finds indisputable evidence that a major terrorist leader is dining right now in a remote farmhouse in central Asia. Say also that local political sensitivities prohibit calling in bombers for an air strike and that the meal is unlikely to last the two hours it would take a Tomahawk cruise missile to reach the site from its maximum range. How to respond?

Pentagon weapons procurers hope to have an answer in an advanced turbine engine that can shrink a cruise missile's "time on target" to "tens of minutes." Such a system might catch the hypothetical terrorist chief before dessert.

The problems posed by highly mobile targets became clear during the first Iraq war, when allied forces had difficulty tracking and hitting truck-mounted Scud-missile launchers. Other armed forces, including Russia's and China's, have supersonic cruise missiles that are powered by ramjets. Unlike a turbine engine, a ramjet does not rely on turbine wheels to compress air for rapid fuel combustion—it simply gulps oncoming air as it travels at high velocity. But these ramjets burn more fuel, have shorter ranges and cannot easily change speeds (be throttled) like the turbine engines in cruise missiles can. In addition, existing long-range supersonic missiles need booster rockets to propel them to speed.

The U.S. Office of Naval Research instead opted to work with Lockheed Martin's Advanced Development Programs ("Skunk Works") and Rolls-Royce's LibertyWorks to build a gas turbine-powered cruise missile that can achieve Mach 3 or more. (Much above Mach 3—in excess of 3,675

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kilometers an hour at sea level—rising turbine temperatures start to damage key components.) Called the Revolutionary Approach to Time-Critical Long-Range Strike program, RATTLRS may yield a cruise missile with much greater operational flexibility and effectiveness than its ramjet-powered predecessors, says Lockheed Martin program manager Craig Johnston.

The new long-range strike weapon would be able to tailor its flight configuration to its mission, he explains. For instance, after launch from an aircraft, surface ship or submarine, a RATTLRS-type missile could loiter near a target until the time for attack was right. Or it might extend its range by cruising to its objective at fuel-efficient low supersonic velocities and then dispense lethal submunitions precisely across a battlefield at subsonic speeds. In a bunker-buster penetrator role, the missile could accelerate to multi-Mach speeds during its final approach.

LOCKHEED MARTIN AERONAUTICS COMPANY

FAST AND FURIOUS: RATTLRS cruise missile, as shown in this mock-up, could set speed records, thanks to a movable air-inlet spike and a novel engine.

A full-size mock-up of the 20-foot-long RATTLRS missile closely resembles the engine nacelle of Lockheed's now retired SR-71 Blackbird spy plane, particularly its moving air-inlet spike and its severely swept wings. Johnston acknowledges that "RATTLRS has a lot of heritage from the SR-71," which could exceed Mach 3. When shifted forward or back, the innovative spike would alter the engine's intake geometry so it could absorb the shock waves in the oncoming supersonic airflow and thus slow it to usable, subsonic velocities. Depending on the Mach number, the air would either be vented away or injected into the Blackbird's engine.

Unseen in the 21-inch-diameter mock-up, however, is the real key to RATTLRS,

A BRIDGE TO SCRAMJETS

Should the RATTLRS project prove successful, the U.S. Department of Defense will most likely try to extend its top speed to Mach 4 by installing an afterburnerlike system called a ramburner. (This system, which creates extra thrust by shooting fuel into a hot jet nozzle, propelled the SR-71 Blackbird to a world speed mark for piloted aircraft.) This type of engine could then provide initial propulsion for hypersonic aircraft and even orbital boosters powered by supersonic combustion ramjets (scramjets), which cannot fly slower than Mach 4. Hence, says U.S. Office of Naval Research program manager Lawrence Ash, RATTLRS would also "demonstrate a class of technologies that would enable space access."

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the highly compact and fuel-efficient YJ102R turbofan engine, which produces six times the specific thrust (pounds of thrust per pound of ingested air) of the SR-71's engine, says LibertyWorks program director Bob Duge. Although the details are classified, Duge attributes most of the engine's performance to its high operating temperature, which requires an "advanced thermal management" system to keep critical parts relatively cool. The burner and the hot turbine blades are made of special temperature-resistant alloys with myriad tiny cooling air passages cast into them.

Johnston says that the U.S. Navy plans to test-fly a prototype missile by the end of 2007 and hopes that a RATTLRS-based missile could be deployed by 2015.

EARTH SCIENCE

Hot Trails

TO FIGHT GLOBAL WARMING, KISS THE RED-EYE GOOD-BYE BY CHRISTINA REED

Air travelers have more to hate about red-eye flights, where sleep is as ephemeral and satisfying as a bag of pretzels for dinner. Those overnight trips contribute more to atmospheric warming than daytime jetting.

Scientists have long known that airplane condensation trails act to both cool and heat the atmosphere. Formed by jet engines' hot exhaust, contrails act as thin cloud barriers that not only reflect sunlight but also prevent the earth's heat from escaping into space. During the day, the effect of blocked incoming radiation tends to outweigh that of trapped heat, thereby cooling the atmosphere. Indeed, after the events of 9/11 grounded all commercial U.S. flights for three days, daytime temperatures across the country rose slightly, whereas nighttime temperatures dropped. This evidence supported the hypothesis that contrails reduce the temperature range by cooling the atmosphere during the day and heating it at night.

Thus, the timing of the flights is critical, but so is the atmosphere itself. Nicola Stuber of the University of Reading in England and her colleagues collected data from weather balloons over a region in southeastern England that lies within the North Atlantic flight corridor. Her team reported in the June 15 *Nature* that even though fewer jets fly during the winter months, the season's higher humidity makes these flights twice as likely to create contrails. The team also found that flying between 6 P.M. and 6 A.M. contributed between 60 and 80 percent of the climate warming that originated from contrails, even though these flights represent a quarter of the total air traffic.

CONTRAILS end up warming the atmosphere.

ANTHONY JOHN WEST *Corbis*

Atmospheric scientist David Travis of the University of Wisconsin–Whitewater, who reported the 9/11-related contrail findings, agrees with the British researchers that a reduction in nighttime flights is needed. He adds that contrails "are currently a regional-scale problem but could eventually become a global-scale problem as air traffic continues to expand and increase." Scientists are only beginning to study the contribution of jet exhaust to global warming, but so far, like red eyes, contrails don't look so good.

Christina Reed flies frequently out of Seattle.

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ROBOTICS

Thinking of Child's Play

BRAIN-MACHINE INTERFACE TURNS ROBOTS INTO GAMERS **BY TIM HORNYAK**

As a time-honored way to make decisions in Japan, adults often resort to *janken,* a local version of the child's game of rock, paper, scissors. Japanese scientists have developed a new twist on this tradition, a machine that can read minds and then form the "weapon" of choice on a mechanical hand—in effect, a mind-controlled robot.

NOT A PEACE SIGN: A mechanical robot hand can form a rock, paper or scissors after being fed data from a player's brain as "read" by an fMRI machine.

The joint project by Kyoto-based Advanced Telecommunications Research (ATR) Institute International and Honda Research Institute Japan is a novel "brain-machine interface." In the ATR-Honda approach, demonstrated this past May, a subject in a functional magnetic resonance imaging (fMRI) machine forms the rock, paper or scissors with his hand. A machine-learning algorithm analyzes the fMRI data on changes in blood flow connected with neural activity in the motor cortex. The decoded data are transmitted to the robot hand, which reproduces the choice within about seven seconds and with 85 percent accuracy.

Although the brain-machine interface might suggest the fantasy of having a personal army of robots controlled simply by mental command, the research is essentially about pattern recognition. "We have been working on methods for decoding brain activity," says cognitive neuroscientist Yukiyasu Kamitani of ATR. "A brain-machine interface is only one of many possible applications of the decoding technique. For instance, if you could decode a person's attitude toward some product, you could use that for marketing." The interface could also lead to a kind of "information terminal," he adds, that would enable thought-guided operation of cell phones and computers. Honda Research Institute's Tatsuhiko Sekiguchi envisions a brain analyzer that would monitor drivers' mental states and warn of drowsiness or inattention.

The ATR-Honda investigators chose functional MRI because it provides the greatest accuracy of all brain-reading strategies, according to Kamitani. "You can get a cross section of the brain," he says. "With MEG [magnetoencephalography] or EEG [electroencephalography], you can get only a map of magnetic or electrical fields on the scalp, and using that you can infer where the current is coming from, but you cannot say for sure where it is. You cannot [directly] get a spatial map." EEG, which is faster but also prone to interference, usually requires intensive user training and special thinking processes to produce activity that can be detected. The fMRI-based approach, though, requires no training, only natural brain activity.

Kamitani's group needs to identify more complex mental activity for its brain-machine interface to become practicable. On the engineering side, the large scanning apparatus would have to be made smaller and lighter, like an electrode cap. Kamitani speculates that by studying accumulated fMRI data, a compact system could be developed that specializes in a certain brain area or mental task. The team is also experimenting with MEG to see if it might be appropriate.

For now, the researchers want to accelerate and improve their decoding technique to detect mere intention in rock, paper, scissors and eliminate the need to physically form the hand shapes. "This game involves some social aspect—you want to win and predict what the other person is doing," Kamitani explains. "We want to decode the intention rather than the actual movement." Perhaps in five to 10 years, suggests Honda Research Institute president Tomohiko Kawanabe, the interface will be good enough to control the automaker's famous Asimo humanoid robot. If so, it's sure to play a mean game of *janken.*

Tim Hornyak, based in Tokyo, is author of Loving the Machine: The Art and Science of Japanese Robots.

MIND READING

To translate thought into robotic actions, Advanced Telecommunications Research and Honda rely on functional magnetic resonance imaging to "read" the mind. But other methods exist. Duke University neurobiologist Miguel Nicolelis, for instance, implanted electrodes in a monkey's brain to manipulate a robot arm. In the hope of helping disabled people communicate, other groups have used electroencephalography (EEG) to translate human thoughts into computer commands via noninvasive means such as caps covered with electrodes. Researchers also experiment with a brain-scanning method using magnetic fields called magnetoencephalography (MEG).

HONDA MOTOR COMPANY

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news SCAN

BY THE NUMBERS

Dumbing Down

THE NEW ILLITERACY—A CHALLENGE TO THE BODY POLITIC? BY RODGER DOYLE

For many years, the U.S. measured literacy simply by asking respondents whether they could read or write, an approach perhaps sufficiently adequate when most people worked with their hands. Using this method, the Census Bureau in 1969 estimated that illiteracy in the U.S. population age 14 and older was only 1 percent.

In 1992 the U.S. Department of Education embarked on a more thorough analysis and mounted a landmark survey. It asked a representative group of 26,091 Americans to read several texts and then had them *demonstrate* that they understood the texts. The department used three types—prose, document and quantitative texts [*see sidebar*]—containing fairly simple material encountered in everyday life. The study was repeated in 2003.

As the table shows, the most heartening and robust statistic to emerge from these surveys was an improvement in African-American scores over the span covered by the two surveys. Other changes were less robust. Women's scores improved while men's declined. Asian-Americans made gains, but Hispanics fell substantially in two of the three categories, possibly reflecting recent immigration from Latin American countries. Test scores fell among all educational groups, including college graduates, perhaps because less proficient young people were drawn into the educational system and the proportion of those 50 and older in the U.S. had increased by 2003. (Older individuals tend to score lower than younger ones.)

A continuing flow of poorly schooled migrants feeds U.S. illiteracy, which helps to explain why the nation has higher illiteracy rates than, say, the Nordic countries, which have relatively few migrants. This stream refreshes the pool of minimally literate Americans. But more than showing that illiteracy has persisted over time, the Department of Education surveys have also revealed its extent across the U.S. population. The 2003 study found that at least 12 percent of those surveyed were classified as having, in the terminology of the report, "below basic" skills, meaning that they could perform no more than the most simple and concrete literacy tasks, such as locating information in short, commonplace texts.

Those in the next higher literacy group, who were labeled as having "basic" skills, account for 22 percent of adults. Though somewhat more literate, they are ill equipped to compete with the better educated. Together the two groups—the "below basic" and the "basic"—make up 34 percent of all adult Americans and should be counted as illiterate by the standards of the information economy. Their illiteracy not only bars them from the better jobs but also limits their participation in political and social life and so contributes to the divisiveness of American society.

PERCENT CHANGE IN ADULT LITERACY SCORES, 1992 TO 2003

	LITERACY TYPE		
	Prose	Document	Quantitative
TOTAL	–0.6	–0.2	+2.6
GENDER			
Male	–1.5*	–1.9*	+1.0
Female	+0.3	+1.5*	+4.0*
RACE, ETHNICITY			
White	+0.4	+0.3	+3.1*
Black	+2.8*	+3.5*	+7.3*
Hispanic	–7.4*	–6.0*	–0.3
Asian, Pacific Islander	+6.2*	+5.1	+6.1
EDUCATIONAL STATUS			
High school graduate	–2.3*	–1.2	+0.7
College graduate	–3.5*	–4.2*	–0.3
Graduate studies, degree	–3.8*	–5.2*	–1.3

**Significantly different from 1992. Group numbers may not sum to the total because of a statistical peculiarity called Simpson's paradox.*

Rodger Doyle can be reached at rodgerpdoyle@verizon.net

RODGER DOYLE; SOURCE: *A FIRST LOOK AT THE LITERACY OF AMERICA'S ADULTS IN THE 21ST CENTURY*, NATIONAL CENTER FOR EDUCATION STATISTICS, WASHINGTON, D.C., 2005

NEED TO KNOW: TYPES OF LITERACY

The U.S. Department of Education surveys tested respondents on three types of reading ability:

Prose Literacy: The skills needed to comprehend and use information from continuous texts such as newspaper articles.

Document Literacy: The knowledge and skills needed to comprehend and use information from noncontinuous texts such as simple statistical tables.

Quantitative Literacy: The knowledge and skills needed to identify and perform computations using numbers embedded in printed materials such as tax forms. Example: Calculating a tip or a loan rate.

FURTHER READING

The Twin Challenges of Mediocrity and Inequality: Literacy in the U.S. from an International Perspective. Andrew Sum, Irwin Kirsch and Robert Taggart. Educational Testing Service, 2002. www.ets.org/Media/Research/pdf/PICTWIN.pdf

A First Look at the Literacy of America's Adults in the 21st Century. National Center for Educational Statistics, December 2005. http://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2006470

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DATA POINTS: PREGNANT WITH IMPLICATIONS

Cesarean sections declined in the seven years following 1989, when U.S. birth certificates first recorded methods of delivery. But recently they have spiked. Proposed explanations include an increase in multiple births and in the number of women more likely to have a C-section, such as those who are older, overweight or diabetic. —*Brie Finegold*

Percent of births delivered by cesarean section in:
2004: 29.1
1996: 20.7
1989: 22.8

Percent increase in twin births, 1990 to 2003: 37.1

Fraction of women in 2003 who gained prepregnancy weight beyond recommended guidelines: 1/3

Percent increase in mothers with diabetes, 1990 to 2003: 40

Percent change in birth rate from 1990 to 2003 for women ages:
20 to 24: –12
35 to 39: 38
40 to 44: 58

SOURCES: Division of Vital Statistics, Centers for Disease Control and Prevention; Institute of Medicine (weight guidelines)

CHEMISTRY

Pre-Plastic Fantastic

Along with rising prices at the pump, the cost of some petroleum-based chemicals used in plastics manufacturing has skyrocketed. Accordingly, researchers have sought to improve a process for turning fructose, a common plant sugar, into 5-hydroxymethylfurfuran (HMF), an alternative, nonpetroleum precursor for chemicals such as polyesters. The reaction occurs in water, which creates several unwanted compounds. To obtain pure HMF, chemists have had to redissolve it in a solvent that is hard to boil away, making the process costly and inefficient. A group from the University of Wisconsin–Madison doubled the reaction's overall yield, to 80 percent, by adding a series of compounds to suppress the reactions that create by-products. Moreover, the additives increase HMF's affinity for a solvent that boils at a low temperature, making the final product easier to obtain. Distill the essentials from the June 30 *Science*. —*JR Minkel*

ASTRONOMY

Direct Gaze

"Men, like planets, have both a visible and an invisible history," wrote George Eliot. Actually, most planets have only an invisible history—we know them only through their indirect influences on the things we do see. Astronomers have yet to make a direct image of a true planet outside our solar system. Michael Liu of the University of Hawaii and his colleagues are now starting the most ambitious search so far, combining a new coronagraph (which masks out the host star), a high-sensitivity adaptive optics system (which de-twinkles the light), and a spectral subtraction technique that wrings out the remaining stellar glare by focusing on emission from methane (which sunlike stars, being too hot, do not contain). A Jupiter-size world in a Jupiter-like orbit around a young star would show up. Not only would direct images reveal bodies that indirect ones do not, they would show much more detail, including atmospheric composition and perhaps even potential signs of life. —*George Musser*

CONSCIOUSNESS

Magical Mushroom Tour

Psychedelic mushrooms have for millennia been said to trigger mystical experiences. The most rigorous scientific experiment with the hallucinogen, and the first in 40 years, proved capable of producing mystical states in the laboratory safely. Scientists at Johns Hopkins University selected 36 spiritually active volunteers, who might interpret the experiences best, and disqualified potential subjects who had a family or personal risk for psychosis or bipolar disorder. One third of volunteers given psilocybin, the mushroom's active compound, described it as the most spiritually meaningful experience of their lives, and about two thirds rated it in their top five. Some side effects occurred: A third admitted significant fear in the hours following their dose, and some felt momentary paranoia. Two months later 79 percent reported moderately or greatly increased well-being or life satisfaction compared with those given a placebo. Further research could lead to therapies against pain, depression or addiction, experts commented online July 12 in *Psychopharmacology*. —*Charles Q. Choi*

THE RIGHT MUSHROOM eaten by the right person can create mystical experiences that yield a lasting sense of well-being.

SCOT FREI *Corbis*; ILLUSTRATION BY MATT COLLINS

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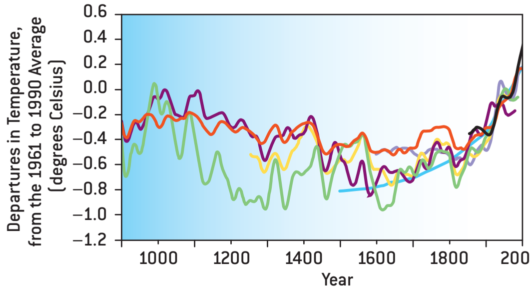
CLIMATE

Support for the Stick

Scientists connected with a 2001 report by the Intergovernmental Panel on Climate Change (IPCC) found in an analysis of Northern Hemisphere temperatures over the past millennium, a sharp rise starting around 1900. Their "hockey stick" graph and conclusion that human activity caused this sudden warming drew fire from politicians and critics. The National Research Council now lends support to the hockey stick. It finds that tree rings, ice cores and other evidence suggest with a high level of confidence that the last decades of the 20th century were warmer than any comparable span in the past four centuries. And like the IPCC work, its report, released June 22, expressed less certainty in temperature reconstructions going back a millennium because of the scarcity of precisely dated evidence before the 17th century. The council noted that the available data did suggest that many locations were hotter in the past 25 years than during any other quarter-century period since the 10th century. —*Charles Q. Choi*



STICK SAVE: A report affirms previous conclusions about past temperatures. Colors represent data provided by various sources, such as ice cores, tree rings and historical documents.

ENERGY

Biodiesel Is Better

Petroleum alternatives include renewable fuels such as biodiesel, derived primarily from soybeans, and ethanol, distilled mostly from corn grain. In the first comprehensive analysis of the energy gains and environmental impact of both fuels, University of Minnesota researchers determined biodiesel to be the better choice. Ethanol from corn grain produces 25 percent more energy than all the energy people invested in it, whereas biodiesel from soybeans returns 93 percent more. Compared with fossil fuels, ethanol produces 12 percent fewer greenhouse gas emissions, whereas biodiesel produces 41 percent fewer. Soybeans also generate significantly less nitrogen, phosphorus and pesticide pollution. Dedicating all current U.S. corn and soybean production to biofuels, however, would meet only 12 percent of gasoline demand and 6 percent of diesel demand. Prairie grass may provide larger biofuel supplies with greater environmental benefits, the scientists reported online July 12 via the *Proceedings of the National Academy of Sciences USA*. —*Charles Q. Choi*

OPTICS

Camera Shy

Digital cameras may soon get disabled via security systems that temporarily blind them. The process exploits a property of the image sensors used by digital cameras—namely, that they are retroreflective, sending light back directly to its origin rather than scattering it. Researchers at the Georgia Institute of Technology developed a prototype that uses light beams and cameras to scan areas for retroreflective dots matching sensors in shape. It then flashes a beam directly at those sensors, overwhelming them. Future versions might use infrared lasers at low, safe energy levels instead of light beams.

The camera-neutralizing technology could thwart clandestine photography or tackle the $3-billion-a-year problem of movie piracy. It would prove ineffective against conventional film cameras, however, or single-lens reflex digital cameras, which use folding mirrors that mask their sensors except when a photograph is actually taken.
—*Charles Q. Choi*

DIGITAL CAMERAS could be blinded remotely.

BRIEF POINTS

- **Prion infections, such as mad cow disease, may incubate without symptoms for years. A technique that amplifies tiny amounts of prions in the blood successfully diagnosed infected hamsters within 20 days after exposure to prions and three months before symptoms appeared.**

  Science, July 7

- **A radar system emits signals that appear as noise to other devices, thus enabling it to escape detection. Properly tuned, the stealth radar can also image objects behind walls.**

  Ohio State University announcement, June 26

- **Abnormal amygdalas may be the root of autism. A postmortem accounting reveals that adult autistic males have about 1.5 million (12 percent) fewer neurons in that brain region, important for memory and emotion.**

  Journal of Neuroscience, July 19

- **The ability to empathize does not appear to be restricted to primates. Mice became more sensitive to pain after having seen cage mates in some distress.**

  Science, June 30

NATIONAL RESEARCH COUNCIL (*top*); YOSHIKAZU TSUNO *AFP/Getty Images* (*bottom*)

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BRAD HINES

Fake, Mistake, Replicate

A court of law may determine the meaning of replication in science By MICHAEL SHERMER

In the rough-and-tumble world of science, disputes are usually settled in time, as a convergence of evidence accumulates in favor of one hypothesis over another. Until now.

On April 10 economist John R. Lott, Jr., formerly of the American Enterprise Institute, filed a defamation lawsuit against economist Steven D. Levitt of the University of Chicago and HarperCollins, the publisher of Levitt's 2005 book, *Freakonomics*. At issue is what Levitt meant when he wrote that scholars could not "replicate" Lott's results, referring to Lott's 1998 book, *More Guns, Less Crime*. Lott employed a sophisticated statistical analysis on data from state-level variation in "carry and conceal" laws, finding that states that passed laws permitting citizens to carry concealed weapons saw statistically significant declines in robbery, rape and homicide compared with states that did not pass such laws.

As is typical with such politically charged research, considerable controversy followed publication of Lott's book, with a flurry of conference presentations and journal papers, some of which replicated his results and some of which did not. For example, in a series of papers published in the *Stanford Law Review* (available at http://papers.ssrn.com), Lott and his critics debated the evidence.

Replicating results means testing hypotheses.

In *Freakonomics,* Levitt proffered his own theory for the source of the 1990s crime decline—*Roe v. Wade*. According to Levitt, children born into impoverished and adverse environments are more likely to land in jail as adults. After *Roe v. Wade,* millions of poor single women had abortions instead of future potential criminals; 20 years later the set of potential offenders had shrunk, along with the crime rate. Levitt employed a comparative statistical analysis to show that the five states that legalized abortion at least two years before *Roe v. Wade* witnessed a crime decline earlier than the other 45 states. Further, those states with the highest abortion rates in the 1970s experienced the greatest fall in crime in the 1990s.

One factor that Levitt dismissed is Lott's, in a single passage in the middle of a 30-page chapter: "Lott's admittedly intriguing hypothesis doesn't seem to be true. When other scholars have tried to replicate his results, they found that right-to-carry laws simply don't bring down crime."

According to Lott's legal complaint, "the term 'replicate' has an objective and factual meaning": that other scholars "have analyzed the identical data that Lott analyzed and analyzed it the way Lott did in order to determine whether they can reach the same result." When Levitt said that they could not, he was "alleging that Lott falsified his results."

I asked Levitt what he meant by "replicate." He replied: "I used the term in the same way that most scientists do—substantiate results." Substantiate, not duplicate. Did he mean to imply that Lott falsified his results? "No, I did not." In fact, others have accused Lott of falsifying his data, so I asked Lott why he is suing Levitt. "Having some virtually unheard-of people making allegations on the Internet is one thing," Lott declared. "Having claims made in a book published by an economics professor and printed by a reputable book publisher, already with sales exceeding a million copies, is something entirely different. In addition, Levitt is well known, and his claims unfortunately carry some weight. I have had numerous people ask me after reading *Freakonomics* whether it is really true that others have been unable to replicate my research."

"Replicate" is a verb that depends on the sentence's object. "Replicate methodology" might capture Lott's meaning, but "replicate results" means testing the conclusion of the methodology, in this case that having more guns in society results in less crime. The problem is that such analyses are so complicated that the failure to replicate more likely indicates modeling mistakes made during the original research or in the replication process rather than fakery.

Mr. Lott, tear down this legal wall and let us return to doing science without lawyers. Replicating results means testing hypotheses—not merely duplicating methodologies—and this central tenet of science can only flourish in an atmosphere of open peer review. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* Science Friction.

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Lower Fertility: A Wise Investment

Plans that encourage voluntary, steep reductions in the fertility rates of poor nations pay dividends in sustainability for everyone

By JEFFREY D. SACHS

The world faces looming ecological threats from the incredible stresses that global economic activity places on our major ecosystems. True, rapid population growth is not the main driver today of these threats. Pride of place goes to the high and rising rates of resource use per person rather than to the rise in the sheer number of people. Even if the total population were to stabilize at today's level of 6.5 billion, the pressures of rising per capita resource use would continue to mount. With the rich countries living at roughly $30,000 per person and the world's average income at around $10,000 per person, simply having the poor catch up with the income levels of the rich would triple global economic throughput, with all the attendant environmental consequences.

Yet the continued rapid population growth in many poor countries will markedly exacerbate the environmental stresses. Under current demographic trends, the United Nations forecasts a rise in the population to around nine billion as of 2050, another 2.5 billion people. They will arrive in the poor regions but aspire to the income and consumption levels of the rest of the world. If the economic aspirations of the newly added population are fulfilled, the environmental pressures will be mind-boggling. If those aspirations are not fulfilled, the political pressures will be similarly mind-boggling.

Four steps can reduce fertility rates dramatically within 15 years.

For the poor countries, the benefits of lowering fertility are apparent. High fertility rates are leading to extreme local environmental pressures—water stress, land degradation, overhunting and overfishing, falling farm sizes, deforestation and other habitat destruction—thereby worsening the grave economic challenges these lands face. High fertility also represents a disaster for the added children themselves, who suffer from profound underinvestments in education, health and nutrition and are thus far more likely to grow up impoverished. In short, a move to lower fertility rates will mean healthier children, much faster growth in living standards and reduced environmental stressors.

Reducing fertility rates in the poorest countries would also be among the smartest investments that the rich countries could make for their own future well-being. Fifty percent of the projected population increase by 2050 will fall within Africa and the Middle East, the planet's most politically and socially unstable regions. That development could well mean another generation of underemployed and frustrated young men, more violence because of joblessness and resource scarcity, more pressures for international migration, and more ideological battles with Europe and the U.S. The global ecological toll could be just as disastrous, because rapid population growth would be taking place in many of the world's "biodiversity hot spots."

Disappointingly, the Bush administration has turned its back on fertility control in poor countries—despite overwhelming evidence that fast, voluntary and highly beneficial transitions to low fertility rates are possible. Such transitions can be promoted through a sensible four-part strategy. First, promote child survival. When parents have the expectation that their children will survive, they choose to have fewer children. Second, promote girls' education and gender equality. Girls in school marry later, and empowered young women enter the labor force and choose to have fewer children. Third, promote the availability of contraception and family planning, especially for the poor who cannot afford such services on their own. Fourth, raise productivity on the farm. Income-earning mothers rear fewer children.

These four steps can reduce fertility rates quickly and dramatically from, say, five or more children per fertile woman to three or fewer within 10 to 15 years, as has occurred in Iran, Tunisia and Algeria. Many African leaders are waking up to this imperative, realizing that their nations cannot surmount their deep economic woes with populations that double every generation. If we in the rich countries would rise to help with this vital task, we would find eager local partners. SA

An expanded version of this essay is available online at www.sciam.com/ontheweb

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Jeffrey D. Sachs is director of the Earth Institute at Columbia University and of the U.N. Millennium Project.

BRUCE GILBERT/EARTH INSTITUTE

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The Net's Real Security Problem

The deepest threats to online security are the weaknesses in the fundamental protocols that run the Internet By TOM LEIGHTON

Even casually savvy computer users these days know to beware of security threats such as viruses, worms, Trojan horses and other malicious bits of code. What few in the public realize, however, is that the Internet is vulnerable to much deeper levels of fraud that exploit fundamental security gaps in the network protocols themselves. These attacks represent a growing menace to personal, corporate and national security that the federal government needs to address urgently.

Consider the defenselessness of the domain name system (DNS), the Internet's version of 411 information. When you type a "www."-style name into your browser software, the browser converts it to an IP address, a string of digits that is the equivalent of a phone number. It does so by contacting a local name server, typically operated by your Internet service provider. Unlike telephone numbers, however, which may be valid indefinitely, IP addresses are valid only for a few seconds, hours or days.

Today's protocols descend from when the Internet was still just a research network.

If a local name server receives a request for an expired DNS name, it in turn queries a hierarchy of other servers, keying its request to two 16-bit identification codes—one for a transaction ID and one for a port number. Unfortunately, the port number is often predictable, so a cyberthief can very likely match both numbers by creating a relatively small number of answers (say, 65,536).

The cyberthief can then ask a local name server for the IP address for XYZ Bank's home page and learn when it will expire. At the moment of expiration, he again asks for the bank's address and immediately sends out the 65,536 answers that list his own computer's IP address as that of the bank. Under the DNS protocol, the local name server simply accepts the first answer that matches its codes; it does not check where the answer came from, and it ignores any additional replies.

So if our hacker gets his answers in first, the local name server will direct customers seeking XYZ Bank to the hacker's computer. Assuming that the hacker runs a convincing imitation of the bank's sign-in page on his computer, customers will not realize that they are handing their confidential information over to a fake.

Similar flaws plague some other critical network protocols as well. Such vulnerabilities imperil more than individuals and commercial institutions. Secure installations in the government and the military can be compromised this way, too. And indeed, there have been cases in which these loopholes did allow data to be stolen and records to be altered.

How did we come to be in such a mess? Today's protocols descend from ones developed 35 years ago, when the Internet was still a research network. There was no need to safeguard the network against malicious entities. Since then, the Internet has opened up and grown explosively, but we have not developed inherently stronger security.

Doing so would be a formidable challenge. For instance, techniques for authenticating that messages come from the proper parties are well developed, but those technologies are not necessarily fast enough to be embedded in all the routers on the Internet without bringing traffic to a crawl. Even worse, Internet users can be tricked into thinking they are protected by such measures while divulging confidential information to a cyberthief. For these reasons and more, in its February 2005 report the President's Information Technology Advisory Committee (of which I was a member) strongly recommended increased federal funding for basic research into cybersecurity.

Cybersecurity needs immediate, sustained attention. The longer we wait to fix the problem, the more we will pay in losses from cybercrime and the greater our exposure to a major attack on our IT infrastructure. SA

An extended version of this essay is available online at www.sciam.com/ontheweb

Tom Leighton is co-founder and chief scientist of Akamai Technologies, Inc., and professor of applied mathematics at the Massachusetts Institute of Technology.

SAM OGDEN/CSAIL MIT

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A Climate Repair Manual

Global warming is a reality. Innovation in energy technology and policy are sorely needed if we are to cope BY GARY STIX

OVERVIEW

- New reports pile up each month about the perils of climate change, including threats to marine life, increases in wildfires, even more virulent poison ivy.
- Implementing initiatives to stem global warming will prove more of a challenge than the Manhattan Project.
- Leading thinkers detail their ideas in the articles that follow for deploying energy technologies to decarbonize the planet.

Explorers attempted and mostly failed over the centuries to establish a pathway from the Atlantic to the Pacific through the icebound North, a quest often punctuated by starvation and scurvy. Yet within just 40 years, and maybe many fewer, an ascending thermometer will likely mean that the maritime dream of Sir Francis Drake and Captain James Cook will turn into an actual route of commerce that competes with the Panama Canal.

The term "glacial change" has taken on a meaning opposite to its common usage. Yet in reality, Arctic shipping lanes would count as one of the more benign effects of accelerated climate change. The repercussions of melting glaciers, disruptions in the Gulf Stream and record heat waves edge toward the apocalyptic: floods, pestilence, hurricanes, droughts—even itchier cases of poison ivy. Month after month, reports mount of the deleterious effects of rising carbon levels. One recent study chronicled threats to coral and other marine organisms, another a big upswing in major wildfires in the western U.S. that have resulted because of warming.

The debate on global warming is over. Present levels of carbon dioxide—nearing 400 parts per million (ppm) in the earth's atmosphere—are higher than they have been at any time in the past 650,000 years and could easily surpass 500 ppm by the year 2050 without radical intervention.

The earth requires greenhouse gases, including water vapor, carbon dioxide and methane, to prevent some of the heat from the received solar radiation from escaping back into space, thus keeping the planet hospitable for protozoa, Shetland ponies and Lindsay Lohan. But too much of a good thing—in particular, carbon dioxide from SUVs and local coal-fired utilities—is causing a steady uptick in the thermometer. Almost all of the 20 hottest years on record have occurred since the 1980s.

No one knows exactly what will happen if things are left unchecked—the exact date when a polar ice sheet will complete a phase change from solid to liquid cannot be foreseen with precision, which is why the Bush ad-

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Carbon emissions are heating the earth.

CARY WOLINSKY (photograph); JEN CHRISTIANSEN (photoillustration)

ministration and warming-skeptical public-interest groups still carry on about the uncertainties of climate change. But no climatologist wants to test what will arise if carbon dioxide levels drift much higher than 500 ppm.

A League of Rations

PREVENTING the transformation of the earth's atmosphere from greenhouse to unconstrained hothouse represents arguably the most imposing scientific and technical challenge that humanity has ever faced. Sustained marshaling of cross-border engineering and political resources over the course of a century or more to check the rise of carbon emissions makes a moon mission or a Manhattan Project appear comparatively straightforward.

Climate change compels a massive restructuring of the world's energy economy. Worries over fossil-fuel supplies reach crisis proportions only when safeguarding the climate is taken into account. Even if oil production peaks soon—a debatable contention given Canada's oil sands, Venezuela's heavy oil and other reserves—coal and its derivatives could tide the earth over for more than a century. But fossil fuels, which account for 80 percent of the world's energy usage, become a liability if a global carbon budget has to be set.

Translation of scientific consensus on climate change into a consensus on what should be done about it carries the debate into the type of political minefield that has often undercut attempts at international governance since the League of Nations. The U.S. holds less than 5 percent of the world's population but produces nearly 25 percent of carbon emissions and has played the role of saboteur by failing to ratify the Kyoto Protocol and commit to reducing greenhouse gas emissions to 7 percent below 1990 levels.

Yet one of the main sticking points for the U.S.—the absence from that accord of a requirement that developing countries agree to firm emission limits—looms as even more of an obstacle as a successor agreement is contemplated to take effect when Kyoto expires in 2012. The torrid economic growth of China and India will elicit calls from industrial nations for restraints on emissions, which will again be met by even more adamant retorts that citizens of Shenzhen and Hyderabad should have the same opportunities to build their economies that those of Detroit and Frankfurt once did.

Kyoto may have been a necessary first step, if only because it lit up the pitted road that lies ahead. But stabilization of carbon emissions will require a more

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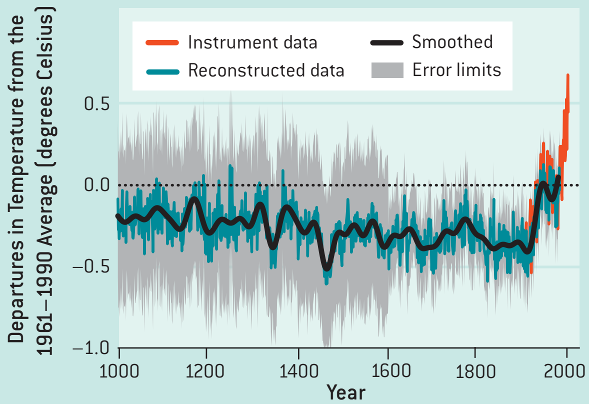
THE HEAT IS ON

A U.S. senator has called global warming the "greatest hoax" ever foisted on the American people. But despite persistently strident rhetoric, skeptics are having an ever harder time making their arguments: scientific support for warming continues to grow.

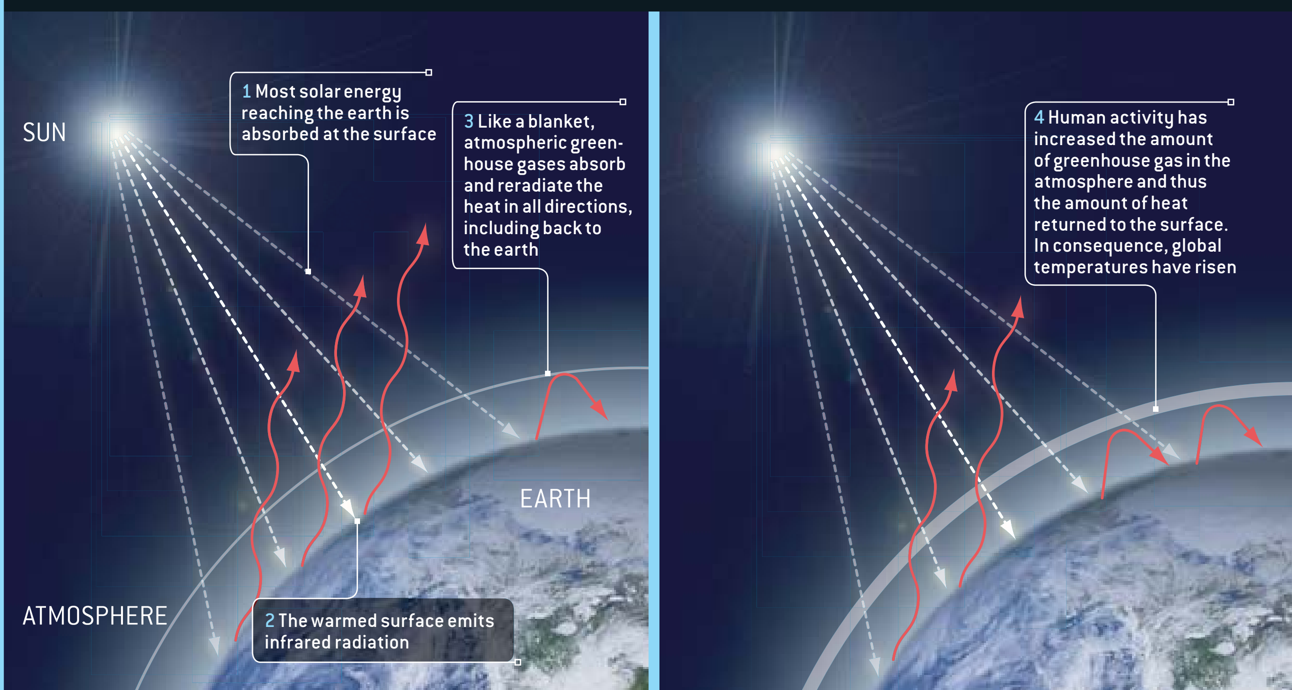


This "hockey stick graph," from one of many studies showing a recent sharp increase in average temperatures, received criticism from warming skeptics, who questioned the underlying data. A report released in June by the National Research Council lends new credence to the sticklike trend line that traces an upward path of temperatures during the 20th century.

A line of SUVs symbolizes high per-capita U.S. energy consumption. But rising expectations pervade the developing world. Many Chinese dream of trading a bicycle for a car.

GREENHOUSE EFFECT

A prerequisite for life on earth, the greenhouse effect occurs when infrared radiation (heat) is retained within the atmosphere.



JEN CHRISTIANSEN, SOURCE: *IPCC THIRD ASSESSMENT REPORT (graph)*; RICHARD MICHAEL PRUITT *Dallas Morning News/Corbis (SUVs)*; FREDERIC J. BROWN *AFP/Getty Images (China)*; LUCY READING-IKKANDA *(illustrations)*

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tangible blueprint for nurturing further economic growth while building a decarbonized energy infrastructure. An oil company's "Beyond Petroleum" slogans will not suffice.

Industry groups advocating nuclear power and clean coal have stepped forward to offer single-solution visions of clean energy. But too much devoted too early to any one technology could yield the wrong fix and derail momentum toward a sustainable agenda for decarbonization. Portfolio diversification underlies a plan laid out by Robert H. Socolow and Stephen W. Pacala in this single-topic edition of *Scientific American*. The two Princeton University professors describe how deployment of a basket of technologies and strategies can stabilize carbon emissions by midcentury.

Perhaps a solar cell breakthrough will usher in the photovoltaic age, allowing both a steel plant and a cell phone user to derive all needed watts from a single source. But if that does not happen—and it probably won't—many technologies (biofuels, solar, hydrogen and nuclear) will be required to achieve a low-carbon energy supply. All these approaches are profiled by leading experts in this special issue, as are more radical ideas, such as solar power plants in outer space and fusion generators, which may come into play should today's seers prove myopic 50 years hence.

▲ Then and now: Sunset Glacier in Alaska's Denali National Park, shown covering a mountainside in August 1939, had all but vanished 65 years later when photographed during the same month.

McINTYRE AP Photo/National Park Service (top); R. D. KARPILO AP Photo/National Park Service (bottom)

No More Business as Usual

PLANNING in 50- or 100-year increments is perhaps an impossible dream. The slim hope for keeping atmospheric carbon below 500 ppm hinges on aggressive programs of energy efficiency instituted by national governments. To go beyond what climate specialists call the "business as usual" scenario, the U.S. must follow Europe and even some of its own state governments in instituting new policies that affix a price on carbon—whether in the form of a tax on emissions or in a cap-and-trade system (emission allowances that are capped in aggregate at a certain level and then traded in open markets). These steps can furnish the breathing space to establish the defense-scale research programs needed to cultivate fossil fuel alternatives. The current federal policy vacuum has prompted a group of eastern states to develop their own cap-and-trade program under the banner of the Regional Greenhouse Gas Initiative.

Fifty-year time frames are planning horizons for futurists, not pragmatic policymakers. Maybe a miraculous new energy technology will simultaneously solve our energy and climate problems during that time, but another scenario is at least as likely: a perceived failure of Kyoto or international bickering over climate questions could foster the burning of abundant coal for electricity and synthetic fuels for transportation, both without meaningful checks on carbon emissions.

A steady chorus of skeptics continues to cast doubt on the massive peer-reviewed scientific literature that forms the cornerstone for a consensus on global warming. "They call it pollution; we call it life," intones a Competitive Enterprise Institute advertisement on the merits of carbon dioxide. Uncertainties about the extent and pace of warming will undoubtedly persist. But the consequences of inaction could be worse than the feared economic damage that has bred overcaution. If we wait for an ice cap to vanish, it will simply be too late. SA

MORE TO EXPLORE

The End of Oil: On the Edge of a Perilous New World. Paul Roberts. Houghton Mifflin, 2004.

Kicking the Carbon Habit. William Sweet. Columbia University Press, 2006.

An Inconvenient Truth. Al Gore. Rodale, 2006.

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▶ Humanity faces a choice between two futures: doing nothing to curb emissions (which poses huge climate risks) and bringing them under control (which has costs but also benefits).

A Plan to Keep Carbon in Check

Getting a grip on greenhouse gases is daunting but doable. The technologies already exist. But there is no time to lose

BY ROBERT H. SOCOLOW AND STEPHEN W. PACALA

OVERVIEW

- Humanity can emit only so much carbon dioxide into the atmosphere before the climate enters a state unknown in recent geologic history and goes haywire. Climate scientists typically see the risks growing rapidly as CO_2 levels approach a doubling of their pre-18th-century value.
- To make the problem manageable, the required reduction in emissions can be broken down into "wedges"—an incremental reduction of a size that matches available technology.

Retreating glaciers, stronger hurricanes, hotter summers, thinner polar bears: the ominous harbingers of global warming are driving companies and governments to work toward an unprecedented change in the historical pattern of fossil-fuel use. Faster and faster, year after year for two centuries, human beings have been transferring carbon to the atmosphere from below the surface of the earth. Today the world's coal, oil and natural gas industries dig up and pump out about seven billion tons of carbon a year, and society burns nearly all of it, releasing carbon dioxide (CO_2). Ever more people are convinced that prudence dictates a reversal of the present course of rising CO_2 emissions.

The boundary separating the truly dangerous consequences of emissions from the merely unwise is probably located near (but below) a doubling of the concentration of CO_2 that was in the atmosphere in the 18th century, before the Industrial Revolution began. Every increase in concentration carries new risks, but avoiding that danger zone would reduce the likelihood of triggering major, irreversible climate changes, such as the disappearance of the Greenland ice cap. Two years ago the two of us provided a simple framework to relate future CO_2 emissions to this goal.

We contrasted two 50-year futures. In one future, the emissions rate continues to grow at the pace of the past 30 years for the next 50 years, reaching 14 billion tons of carbon a year in 2056. (Higher or lower rates are, of course, plausible.) At that point, a tripling of preindustrial carbon concentrations would be very difficult to avoid, even with concerted efforts to decarbonize the world's energy systems over the following 100 years. In the other future, emissions are frozen at the present value of seven billion tons a year for the next 50 years and then reduced by about half over the following 50 years. In this way, a doubling of CO_2 levels can be avoided. The difference between these 50-year emission paths—one ramping up and one flattening out—we called the stabilization triangle [*see box on page 52*].

To hold global emissions constant while the world's economy continues to grow is a daunting task. Over the past 30 years, as the gross world

KENN BROWN

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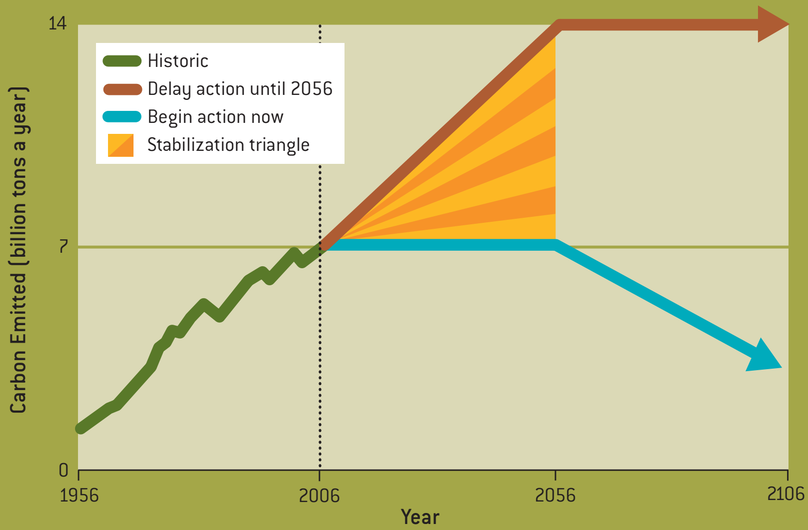
MANAGING THE CLIMATE PROBLEM

At the present rate of growth, emissions of carbon dioxide will double by 2056 (*below left*). Even if the world then takes action to level them off, the atmospheric concentration of the gas will be headed above 560 parts per million, double the preindustrial value (*below right*)—a level widely regarded as capable of triggering severe climate changes. But if the world flattens out emissions beginning now and later ramps them down, it should be able to keep concentration substantially below 560 ppm.

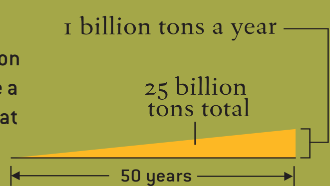
ANNUAL EMISSIONS

In between the two emissions paths is the "stabilization triangle." It represents the total emissions cut that climate-friendly technologies must achieve in the coming 50 years.



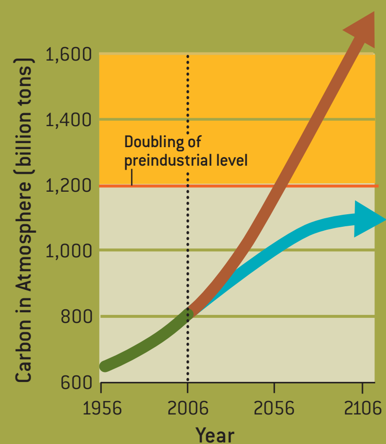
THE WEDGE CONCEPT

The stabilization triangle can be divided into seven "wedges," each a reduction of 25 billion tons of carbon emissions over 50 years. The wedge has proved to be a useful unit because its size and time frame match what specific technologies can achieve. Many combinations of technologies can fill the seven wedges.



CUMULATIVE AMOUNT

Each part per million of CO_2 corresponds to a total of 2.1 billion tons of atmospheric carbon. Therefore, the 560-ppm level would mean about 1,200 billion tons, up from the current 800 billion tons. The difference of 400 billion tons actually allows for roughly 800 billion tons of emissions, because half the CO_2 emitted into the atmosphere enters the planet's oceans and forests. The two concentration trajectories shown here match the two emissions paths at the left.



product of goods and services grew at close to 3 percent a year on average, carbon emissions rose half as fast. Thus, the ratio of emissions to dollars of gross world product, known as the carbon intensity of the global economy, fell about 1.5 percent a year. For global emissions to be the same in 2056 as today, the carbon intensity will need to fall not half as fast but fully as fast as the global economy grows.

Two long-term trends are certain to continue and will help. First, as societies get richer, the services sector—education, health, leisure, banking and so on—grows in importance relative to energy-intensive activities, such as steel production. All by itself, this shift lowers the carbon intensity of an economy.

Second, deeply ingrained in the patterns of technology evolution is the substitution of cleverness for energy. Hundreds of power plants are not needed today because the world has invested in much more efficient refrigerators, air conditioners and motors than were available two decades ago. Hundreds of oil and gas fields have been developed more slowly because aircraft engines consume less fuel and the windows in gas-heated homes leak less heat.

The task of holding global emissions constant would be out of reach, were it not for the fact that all the driving and flying in 2056 will be in vehicles not yet designed, most of the buildings that will be around then are not yet built, the locations of many of the communities that will contain these buildings and determine their inhabitants' commuting patterns have not yet been chosen, and utility owners are only now beginning to plan for the power plants that will be needed to light up those communities. Today's notoriously inefficient energy system can be replaced if the world gives unprecedented attention to energy efficiency. Dramatic changes are plausible over the next 50 years because so much of the energy canvas is still blank.

To make the task of reducing emis-

JEN CHRISTIANSEN

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sions vivid, we sliced the stabilization triangle into seven equal pieces, or "wedges," each representing one billion tons a year of averted emissions 50 years from now (starting from zero today). For example, a car driven 10,000 miles a year with a fuel efficiency of 30 miles per gallon (mpg) emits close to one ton of carbon annually. Transport experts predict that two billion cars will be zipping along the world's roads in 2056, each driven an average of 10,000 miles a year. If their average fuel efficiency were 30 mpg, their tailpipes would spew two billion tons of carbon that year. At 60 mpg, they would give off a billion tons. The latter scenario would therefore yield one wedge.

Wedges

IN OUR FRAMEWORK, you are allowed to count as wedges only those differences in two 2056 worlds that result from deliberate carbon policy. The current pace of emissions growth already includes some steady reduction in carbon intensity. The goal is to reduce it even more. For instance, those who believe that cars will average 60 mpg in 2056 even in a world that pays no attention to carbon cannot count this improvement as a wedge, because it is already implicit in the baseline projection.

Moreover, you are allowed to count only strategies that involve the scaling up of technologies already commercialized somewhere in the world. You are not allowed to count pie in the sky. Our goal in developing the wedge framework was to be pragmatic and realistic—to propose engineering our way out of the problem and not waiting for the cavalry to come over the hill. We argued that even with these two counting rules, the world can fill all seven wedges, and in several different ways [*see box on next page*]. Individual countries—operating within a framework of international cooperation—will decide which wedges to pursue, depending on their institutional and economic capacities, natural resource endowments and political predilections.

To be sure, achieving nearly every one of the wedges requires new science and engineering to squeeze down costs and address the problems that inevitably accompany widespread deployment of new technologies. But holding CO_2 emissions in 2056 to their present rate, without choking off economic growth, is a desirable outcome within our grasp.

Ending the era of conventional coal-fired power plants is at the very top of the decarbonization agenda. Coal has become more competitive as a source of power and fuel because of energy security concerns and because of an increase in the cost of oil and gas. That is a problem because a coal power plant burns twice as much carbon per unit of electricity as a natural gas plant. In the absence of a concern about carbon, the world's coal utilities could build a few thousand large (1,000-megawatt) conventional coal plants in the next 50 years. Seven hundred such plants emit one wedge's worth of carbon. Therefore, the world could take some big steps toward the target of freezing emissions by not building those plants. The time to start is now. Facilities built in this decade could easily be around in 2056.

> Holding carbon dioxide emissions constant for 50 years, without choking off economic growth, is within our grasp.

Efficiency in electricity use is the most obvious substitute for coal. Of the 14 billion tons of carbon emissions projected for 2056, perhaps six billion will come from producing power, mostly from coal. Residential and commercial buildings account for 60 percent of global electricity demand today (70 percent in the U.S.) and will consume most of the new power. So cutting buildings' electricity use in half—by equipping them with superefficient lighting and appliances—could lead to two wedges. Another wedge would be achieved if industry finds additional ways to use electricity more efficiently.

Decarbonizing the Supply

EVEN AFTER energy-efficient technology has penetrated deeply, the world will still need power plants. They can be coal plants but they will need to be carbon-smart ones that capture the CO_2 and pump it into the ground [see "Can We Bury Global Warming?" by Robert H. Socolow; SCIENTIFIC AMERICAN, July 2005]. Today's high oil prices are lowering the cost of the transition to this technology, because captured CO_2 can often be sold to an oil company that injects it into oil fields to squeeze out more oil; thus, the higher the price of oil, the more valuable the captured CO_2. To achieve one wedge, utilities need to equip 800 large coal plants to capture and store nearly all the CO_2 otherwise emitted. Even in a carbon-constrained world, coal mining and coal power can stay in business, thanks to carbon capture and storage.

The large natural gas power plants operating in 2056 could capture and store their CO_2, too, perhaps accounting for yet another wedge. Renewable and nuclear energy can contribute as well. Renewable power can be produced from sunlight directly, either to energize photovoltaic cells or, using focusing mirrors,

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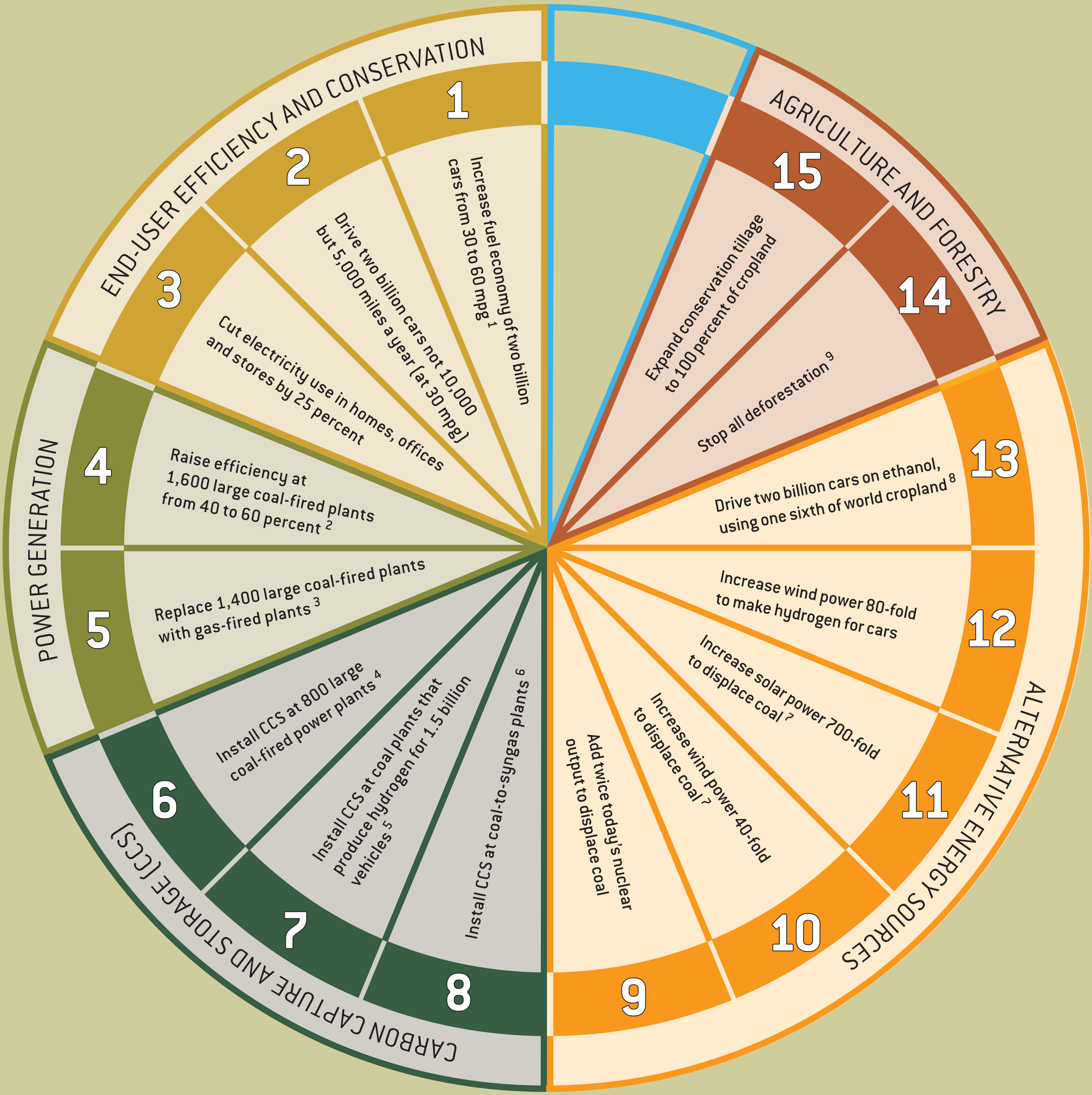
15 WAYS TO MAKE A WEDGE

An overall carbon strategy for the next half a century produces seven wedges' worth of emissions reductions. Here are 15 technologies from which those seven can be chosen (taking care to avoid double-counting). Each of these measures, when phased in over 50 years, prevents the release of 25 billion tons of carbon. Leaving one wedge blank symbolizes that this list is by no means exhaustive.



Notes:

[1] World fleet size in 2056 could well be two billion cars. Assume they average 10,000 miles a year.
[2] "Large" is one-gigawatt (GW) capacity. Plants run 90 percent of the time.
[3] Here and below, assume coal plants run 90 percent of the time at 50 percent efficiency. Present coal power output is equivalent to 800 such plants.
[4] Assume 90 percent of CO_2 is captured.
[5] Assume a car (10,000 miles a year, 60 miles per gallon equivalent) requires 170 kilograms of hydrogen a year.
[6] Assume 30 million barrels of synfuels a day, about a third of today's total oil production. Assume half of carbon originally in the coal is captured.
[7] Assume wind and solar produce, on average, 30 percent of peak power. Thus replace 2,100 GW of 90-percent-time coal power with 2,100 GW (peak) wind or solar plus 1,400 GW of load-following coal power, for net displacement of 700 GW.
[8] Assume 60-mpg cars, 10,000 miles a year, biomass yield of 15 tons a hectare, and negligible fossil-fuel inputs. World cropland is 1,500 million hectares.
[9] Carbon emissions from deforestation are currently about two billion tons a year. Assume that by 2056 the rate falls by half in the business-as-usual projection and to zero in the flat path.

JANET CHAO

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to heat a fluid and drive a turbine. Or the route can be indirect, harnessing hydropower and wind power, both of which rely on sun-driven weather patterns. The intermittency of renewable power does not diminish its capacity to contribute wedges; even if coal and natural gas plants provide the backup power, they run only part-time (in tandem with energy storage) and use less carbon than if they ran all year. Not strictly renewable, but also usually included in the family, is geothermal energy, obtained by mining the heat in the earth's interior. Any of these sources, scaled up from its current contribution, could produce a wedge. One must be careful not to double-count the possibilities; the same coal plant can be left unbuilt only once.

Nuclear power is probably the most controversial of all the wedge strategies. If the fleet of nuclear power plants were to expand by a factor of five by 2056, displacing conventional coal plants, it would provide two wedges. If the current fleet were to be shut down and replaced with modern coal plants without carbon capture and storage, the result would be *minus* one-half wedge. Whether nuclear power will be scaled up or down will depend on whether governments can find political solutions to waste disposal and on whether plants can run without accidents. (Nuclear plants are mutual hostages: the world's least well-run plant can imperil the future of all the others.) Also critical will be strict rules that prevent civilian nuclear technology from becoming a stimulus for nuclear weapons development. These rules will have to be uniform across all countries, so as to remove the sense of a double standard that has long been a spur to clandestine facilities.

Oil accounted for 43 percent of global carbon emissions from fossil fuels in 2002, while coal accounted for 37 percent; natural gas made up the remainder. More than half the oil was used for transport. So smartening up electricity production alone cannot fill the stabilization triangle; transportation, too, must be decarbonized. As with coal-fired electricity, at least a wedge may be available from each of three complementary options: reduced use, improved efficiency and decarbonized energy sources. People can take fewer unwanted trips (telecommuting instead of vehicle commuting) and pursue the travel they cherish (adventure, family visits) in fuel-efficient vehicles running on low-carbon fuel. The fuel can be a product of crop residues or dedicated crops, hydrogen made from low-carbon electricity, or low-carbon electricity itself, charging an onboard battery. Sources of the low-carbon electricity could include wind, nuclear power, or coal with capture and storage.

Looming over this task is the prospect that, in the interest of energy security, the transport system could become *more* carbon-intensive. That will happen if transport fuels are derived from coal instead of petroleum. Coal-based synthetic fuels, known as synfuels, provide a way to reduce global demand for oil, lowering its cost and decreasing global dependence on Middle East petroleum. But it is a decidedly climate-unfriendly strategy. A synfuel-powered car emits the same amount of CO_2 as a gasoline-powered car, but synfuel fabrication from coal spews out far more carbon than does refining gasoline from crude oil—enough to double the emissions per mile of driving. From the perspective of mitigating climate change, it is fortunate that the emissions at a synfuels plant can be captured and stored.

39 percent
U.S. share of global carbon emissions in 1952

23 percent
U.S. share in 2002

The U.S. share of global emissions can be expected to continue to drop.

If business-as-usual trends did lead to the widespread adoption of synfuel, then capturing CO_2 at synfuels plants might well produce a wedge.

Not all wedges involve new energy technology. If all the farmers in the world practiced no-till agriculture rather than conventional plowing, they would contribute a wedge. Eliminating deforestation would result in two wedges, if the alternative were for deforestation to continue at current rates. Curtailing emissions of methane, which today contribute about half as much to greenhouse warming as CO_2, may provide more than one wedge: needed is a deeper understanding of the anaerobic biological emissions from cattle, rice paddies and irrigated land. Lower birth rates can produce a wedge, too—for example, if they hold the global population in 2056 near eight billion people when it otherwise would have grown to nine billion.

Action Plan

WHAT SET OF POLICIES will yield seven wedges? To be sure, the dramatic changes we anticipate in the fossil-fuel system, including routine use of CO_2 capture and storage, will require institutions that reliably communicate a price for present and future carbon emissions. We estimate that the price needed to jump-start this transition is in the ballpark of \$100 to \$200 per ton of carbon—the range that would make it cheaper for owners of coal plants to capture and store CO_2 rather than vent it. The price might fall as technologies climb the learning curve. A carbon emissions price of \$100 per ton is comparable to the current U.S. production credit for new renewable and nuclear energy relative to coal, and it is about half the current U.S. subsidy of ethanol relative to gasoline. It also was the price of CO_2 emissions in the European Union's emissions trading system for nearly a year, spanning 2005 and 2006. (One ton of carbon is carried in 3.7 tons of carbon dioxide, so this price is also \$27 per ton of CO_2.) Based on carbon content, \$100 per ton of carbon is \$12 per barrel of oil and \$60 per ton of coal. It is 25 cents per gallon of gasoline and two cents per

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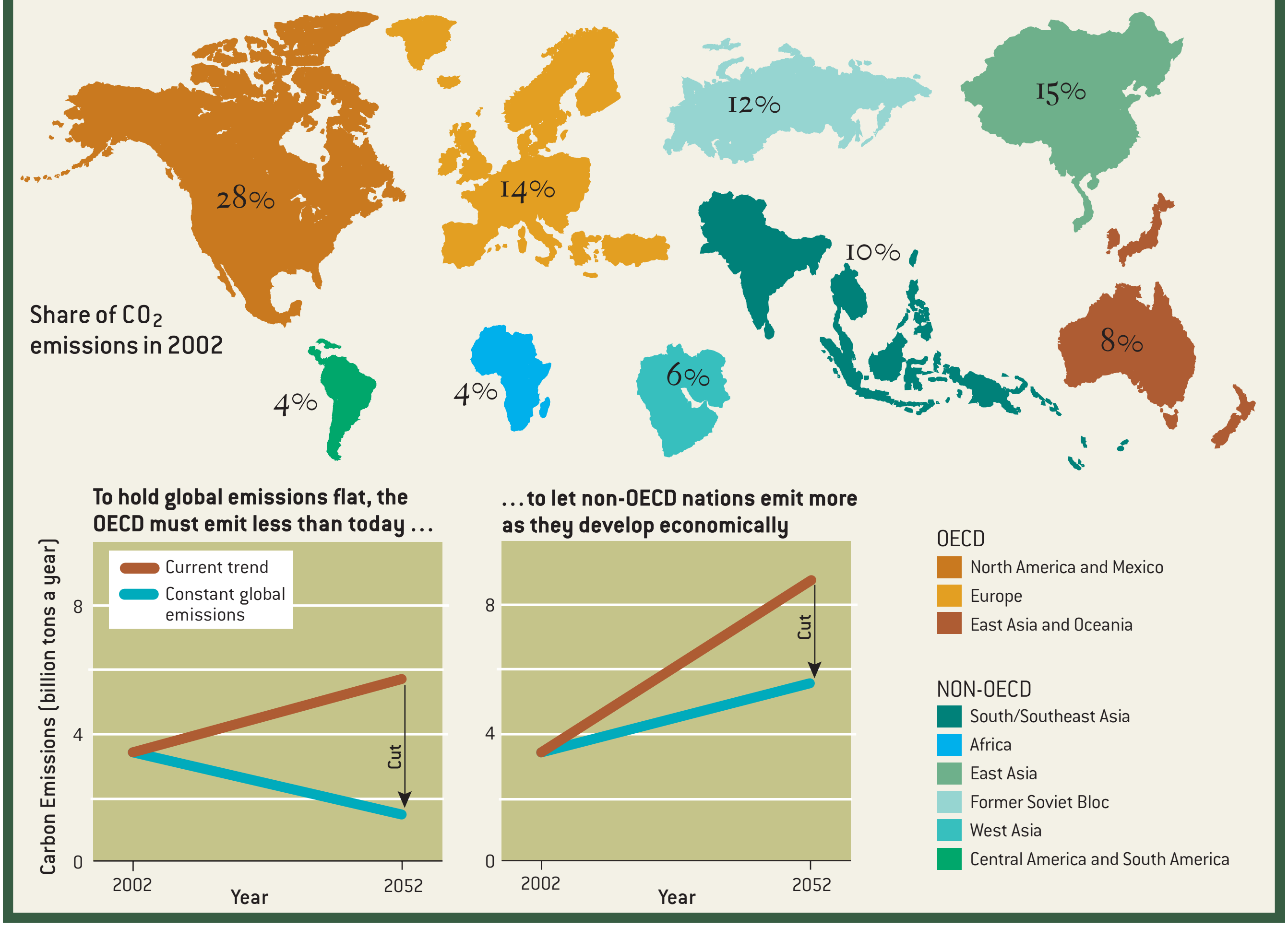
RICH WORLD, POOR WORLD

To keep global emissions constant, both developed nations (defined here as members of the Organization for Economic Cooperation and Development, or OECD) and developing nations will need to cut their emissions relative to what they would have been (*arrows in graphs below*). The projections shown represent only one path the world could take; others are also plausible.



JEN CHRISTIANSEN; SOURCE: "GLOBAL, REGIONAL, AND NATIONAL FOSSIL FUEL CO_2 EMISSIONS," BY G. MARLAND, T. A. BODEN AND R. J. ANDRES, IN *TRENDS: A COMPENDIUM OF DATA ON GLOBAL CHANGE.* CARBON DIOXIDE INFORMATION ANALYSIS CENTER, OAK RIDGE NATIONAL LABORATORY, 2006

kilowatt-hour of electricity from coal.

But a price on CO_2 emissions, on its own, may not be enough. Governments may need to stimulate the commercialization of low-carbon technologies to increase the number of competitive options available in the future. Examples include wind, photovoltaic power and hybrid cars. Also appropriate are policies designed to prevent the construction of long-lived capital facilities that are mismatched to future policy. Utilities, for instance, need to be encouraged to invest in CO_2 capture and storage for new coal power plants, which would be very costly to retrofit later. Still another set of policies can harness the capacity of energy producers to promote efficiency—motivating power utilities to care about the installation and maintenance of efficient appliances, natural gas companies to care about the buildings where their gas is burned, and oil companies to care about the engines that run on their fuel.

To freeze emissions at the current level, if one category of emissions goes up, another must come down. If emissions from natural gas increase, the combined emissions from oil and coal must decrease. If emissions from air travel climb, those from some other economic sector must fall. And if today's poor countries are to emit more, today's richer countries must emit less.

How much less? It is easy to bracket the answer. Currently the industrial nations—the members of the Organization for Economic Cooperation and Development (OECD)—account for almost exactly half the planet's CO_2 emissions, and the developing countries plus the nations formerly part of the Soviet Union account for the other half. In a world of constant total carbon emissions, keeping the OECD's share at 50 percent seems impossible to justify in the face of the enormous pent-up demand for energy in the non-OECD countries, where more than 80 percent of the world's people live. On the other hand, the OECD member states must emit *some* carbon in 2056. Simple arithmetic indicates that to hold global emissions rates steady, non-OECD emissions cannot even double.

One intermediate value results if all OECD countries were to meet the emissions-reduction target for the U.K. that

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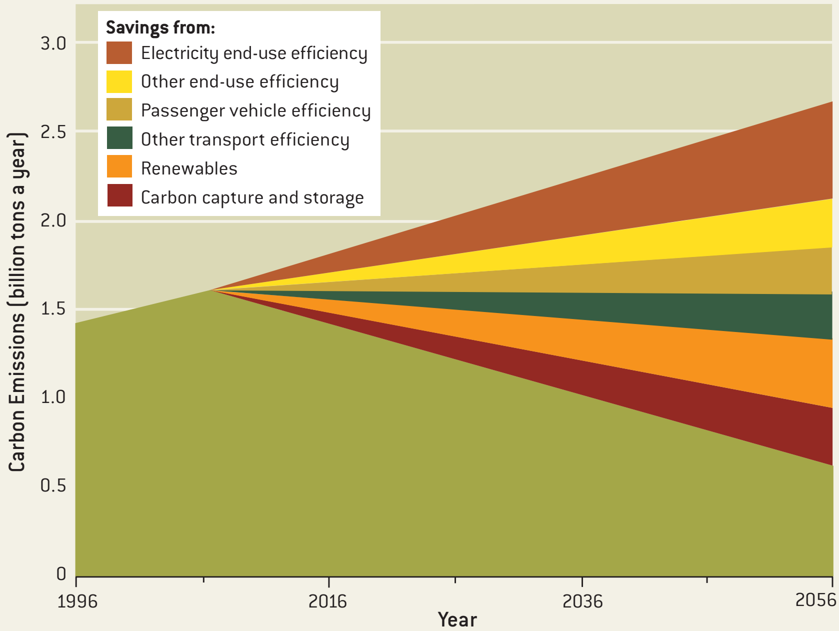
was articulated in 2003 by Prime Minister Tony Blair—namely, a 60 percent reduction by 2050, relative to recent levels. The non-OECD countries could then emit 60 percent more CO_2. On average, by midcentury they would have one half the per capita emissions of the OECD countries. The CO_2 output of every country, rich or poor today, would be well below what it is generally projected to be in the absence of climate policy. In the case of the U.S., it would be about four times less.

Blair's goal would leave the average American emitting twice as much as the world average, as opposed to five times as much today. The U.S. could meet this goal in many ways [*see illustration at right*]. These strategies will be followed by most other countries as well. The resultant cross-pollination will lower every country's costs.

Fortunately, the goal of decarbonization does not conflict with the goal of eliminating the world's most extreme poverty. The extra carbon emissions produced when the world's nations accelerate the delivery of electricity and modern cooking fuel to the earth's poorest people can be compensated for by, at most, one fifth of a wedge of emissions reductions elsewhere.

ONE PLAN FOR THE U.S.



▲ U.S. share of emissions reductions could, in this Natural Resources Defense Council scenario, be achieved by efficiency gains, renewable energy and clean coal.

Beyond 2056

THE STABILIZATION triangle deals only with the first 50-year leg of the future. One can imagine a relay race made of 50-year segments, in which the first runner passes a baton to the second in 2056. Intergenerational equity requires that the two runners have roughly equally difficult tasks. It seems to us that the task we have given the second runner (to cut the 2056 emissions rate in half between 2056 and 2106) will not be harder than the task of the first runner (to keep global emissions in 2056 at present levels)—provided that between now and 2056 the world invests in research and development to get ready. A vigorous effort can prepare the revolutionary technologies that will give the second half of the century a running start. Those options could include scrubbing CO_2 directly from the air, carbon storage in minerals, nuclear fusion, nuclear thermal hydrogen, and artificial photosynthesis. Conceivably, one or more of these technologies may arrive in time to help the first runner, although, as we have argued, the world should not count on it.

As we look back from 2056, if global emissions of CO_2 are indeed no larger than today's, what will have been accomplished? The world will have confronted energy production and energy efficiency at the consumer level, in all economic sectors and in economies at all levels of development. Buildings and lights and refrigerators, cars and trucks and planes, will be transformed. Transformed, also, will be the ways we use them.

The world will have a fossil-fuel energy system about as large as today's but one that is infused with modern controls and advanced materials and that is almost unrecognizably cleaner. There will be integrated production of power, fuels and heat; greatly reduced air and water pollution; and extensive carbon capture and storage. Alongside the fossil energy system will be a nonfossil energy system approximately as large. Extensive direct and indirect harvesting of renewable energy will have brought about the revitalization of rural areas and the reclamation of degraded lands. If nuclear power is playing a large role, strong international enforcement mechanisms will have come into being to control the spread of nuclear technology from energy to weapons. Economic growth will have been maintained; the poor and the rich will both be richer. And our descendants will not be forced to exhaust so much treasure, innovation and energy to ward off rising sea level, heat, hurricanes and drought.

Critically, a planetary consciousness will have grown. Humanity will have learned to address its collective destiny—and to share the planet. SA

MORE TO EXPLORE

Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. S. Pacala and R. Socolow in *Science,* Vol. 305, pages 968–972; August 13, 2004.

The calculations behind the individual wedges are available at **www.princeton.edu/~cmi**

Energy statistics are available at **www.eia.doe.gov, www.iea.org** and **www.bp.com;** carbon emissions data can also be found at **cdiac.esd.ornl.gov**

JEN CHRISTIANSEN; SOURCE: DANIEL A. LASHOF AND DAVID G. HAWKINS *Natural Resources Defense Council*

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Fueling Our Transportation Fu

What are the options for decreasing demand for oil and lowering greenhouse gas emissions in cars and light trucks? **BY JOHN B. HEYWOOD**

If we are honest, most of us in the world's richer countries would concede that we like our transportation systems. They allow us to travel when we want to, usually door-to-door, alone or with family and friends, and with our baggage. The mostly unseen freight distribution network delivers our goods and supports our lifestyle. So why worry about the future and especially about how the energy that drives our transportation might be affecting our environment?

The reason is the size of these systems and their seemingly inexorable growth. They use petroleum-based fuels (gasoline and diesel) on an unimaginable scale. The carbon in these fuels is oxidized to the greenhouse gas carbon dioxide during combustion, and their massive use means that the amount of carbon dioxide entering the atmosphere is likewise immense. Transportation accounts for 25 percent of worldwide greenhouse gas emissions. As the countries in the developing world rapidly motorize, the increasing global demand for fuel will pose one of the biggest challenges to controlling the concentration of greenhouse gases in the atmosphere. The U.S. light-duty vehicle fleet (automobiles, pickup trucks, SUVs, vans and small trucks) currently consumes 150 billion gallons (550 billion liters) of gasoline a year, or 1.3 gallons of gasoline per person a day. If other nations burned gasoline at the same rate, world consumption would rise by a factor of almost 10.

As we look ahead, what possibilities do we have for making transportation much more sustainable, at an acceptable cost?

Our Options

SEVERAL OPTIONS could make a substantial difference. We could improve or change vehicle technology; we could change how we use our vehicles; we could reduce the size of our vehicles; we could use different fuels. We will most likely have to do all of these to drastically reduce energy consumption and greenhouse gas emissions.

In examining these alternatives, we have to keep in mind several aspects of the existing transportation system. First, it is well suited to its primary context, the developed world. Over decades, it has had time to evolve so that it balances economic costs with users' needs and wants. Second, this vast optimized system relies completely on one convenient source of energy—petroleum. And it has evolved technologies—internal-combustion engines on land and jet engines (gas turbines) for air—that well match vehicle operation with this energy-dense liquid fuel. Finally, these vehicles last a long time. Thus, rapid change is doubly difficult. Constraining and then reducing the local and global impacts of transportation energy will take decades.

We also need to keep in mind that efficiency ratings can be misleading; what counts is the fuel

OVERVIEW

- The massive use of petroleum-based fuels for transportation releases immense amounts of carbon dioxide into the atmosphere—25 percent of the total worldwide.
- Options for constraining and eventually reducing these emissions include improving vehicle technology, reducing vehicle size, developing different fuels, and changing the way vehicles are used.
- To succeed, we will most likely have to follow through on all of these choices.

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▲ Concept car from Volkswagen was designed to carry two people around cities and suburbs. Weighing 640 pounds (290 kilograms), the vehicle, which at present exists only as a prototype, gets some 240 miles to the gallon.

VOLKSWAGEN

consumed in actual driving. Today's gasoline spark-ignition engine is about 20 percent efficient in urban driving and 35 percent efficient at its best operating point. But many short trips with a cold engine and transmission, amplified by cold weather and aggressive driving, significantly worsen fuel consumption, as do substantial time spent with the engine idling and losses in the transmission. These real-world driving phenomena reduce the engine's average efficiency so that only about 10 percent of the chemical energy stored in the fuel tank actually drives the wheels. Amory Lovins, a strong advocate for much lighter, more efficient vehicles, has stated it this way: with a 10 percent efficient vehicle and with the driver, a passenger and luggage—a payload of some 300 pounds, about 10 percent of the vehicle weight—"only 1 percent of the fuel's energy in the vehicle tank actually moves the payload."

We must include in our accounting what it takes to produce and distribute the fuel, to drive the vehicle through its lifetime of 150,000 miles (240,000 kilometers) and to manufacture, maintain and dispose of the vehicle. These three phases of vehicle operation are often called well-to-tank (this phase accounts for about 15 percent of the total lifetime energy use and greenhouse gas emissions), tank-to-wheels (75 percent), and cradle-to-grave (10 percent). Surprisingly, the energy required to produce the fuel and the vehicle is not negligible. This total life-cycle accounting becomes especially important as we consider fuels that do not come from petroleum and new types of vehicle technologies. It is what gets used and emitted in this *total sense* that matters.

Improving existing light-duty vehicle technology can do a lot. By investing more money in increasing the efficiency of the engine and transmission, decreasing weight, improving tires and reducing drag, we can bring down fuel consumption by about one third over the next 20 or so years—an annual 1 to 2 percent improvement, on average. (This reduction would cost between $500 and $1,000 per vehicle; at likely future fuel prices, this amount would not increase the lifetime cost of ownership.) These types of improvements have occurred steadily over the past 25 years, but we have bought larger, heavier, faster cars and light trucks and thus have effectively traded the benefits we could have realized for these other attributes. Though most obvious in the U.S., this shift to larger, more powerful vehicles has occurred elsewhere as well.

DAILY USE OF PETROLEUM WORLDWIDE

At present, consumers use 80 million barrels a day (MBD) of petroleum (a barrel contains 42 U.S. gallons). Two thirds of this goes to transportation.

53	29	19	5
MBD for transportation overall	MBD for land transport for people	MBD for land transport for freight	MBD for air transport for people and freight

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We need to find ways to motivate buyers to use the potential for reducing fuel consumption and greenhouse gas emissions to actually save fuel and contain emissions.

In the near term, if vehicle weight and size can be reduced and if both buyers and manufacturers can step off the ever increasing horsepower/performance path, then in the developed world we may be able to slow the rate of petroleum demand, level it off in 15 to 20 years at about 20 percent above current demand, and start on a slow downward path. This projection may not seem nearly aggressive enough. It is, however, both challenging to achieve and very different from our current trajectory of steady growth in petroleum consumption at about 2 percent a year.

In the longer term, we have additional options. We could develop alternative fuels that would displace at least some petroleum. We could turn to new propulsion systems that use hydrogen or electricity. And we could go much further in designing and encouraging acceptance of smaller, lighter vehicles.

The alternative fuels option may be difficult to implement unless the alternatives are compatible with the existing distribution system. Also, our current fuels are liquids with a high-energy density: lower-density fuels will require larger fuel tanks or provide less range than today's roughly 400 miles. From this perspective, one alternative that stands out is nonconventional petroleum (oil or tar sands, heavy oil, oil shale, coal). Processing these sources to yield "oil," however, requires large amounts of other forms of energy, such as natural gas and electricity. Thus, the processes used emit substantial amounts of greenhouse gases and have other environmental impacts. Further, such processing calls for big capital investments. Nevertheless, despite the broader environmental consequences, nonconventional petroleum sources are already starting to be exploited; they are expected to provide some 10 percent of transportation fuels within the next 20 years.

Biomass-based fuels such as ethanol and biodiesel, which are often considered to emit less carbon dioxide per unit of energy, are also already being produced. In Brazil ethanol made from sugarcane constitutes some 40 percent of transport fuel. In the U.S. roughly 20 percent of the corn crop is being converted to ethanol. Much of this is blended with gasoline at the 10 percent level in so-called reformulated (cleaner-burning) gasolines. The recent U.S. national energy policy act plans to double ethanol production from the current 2 percent of transportation fuel by 2012. But the fertilizer, water, and natural gas and electricity currently expended in ethanol production from corn will need to be substantially decreased. Production of ethanol from cellulosic biomass (residues and wastes from plants not generally used as a food source) promises to be more efficient and to lower greenhouse gas emissions. It is not yet a commercially viable process, although it may well become so. Biodiesel can be made from various crops (rapeseed, sunflower, soybean oils) and waste animal fats. The small amounts now being made are blended with standard diesel fuel.

It is likely that the use of biomass-based fuels will steadily grow. But given the uncertainty about the environmental impacts of large-scale conversion of biomass crops to fuel (on soil quality, water resources and overall greenhouse gas emissions), this source will contribute but is unlikely to dominate the future fuel supply anytime soon.

Use of natural gas in transportation varies around the world from less than 1 percent to 10 to 15 percent in a few countries where tax policies make it economical. In the 1990s natural gas made inroads into U.S. municipal bus fleets to achieve lower emissions; diesels with effective exhaust cleanup are now proving a cheaper option.

What about new propulsion system technology? Likely innovations would include significantly improved gasoline engines (using a turbocharger with direct fuel injection, for ex-

TIMESCALES FOR NEW TECHNOLOGIES

New designs for vehicles may eventually bring down overall energy consumption for transportation in the U.S., but they do not offer a quick fix. Estimates from M.I.T.'s Laboratory for Energy and the Environment indicate how long it might take for new technologies to have a significant impact.

	IMPLEMENTATION PHASE			
VEHICLE TECHNOLOGY	Market competitive vehicle	Penetration across new vehicle production*	Major fleet penetration †	Total time for impact
Turbocharged gasoline engine	5 years	10 years	10 years	20 years
Low-emissions diesel	5 years	15 years	10–15 years	30 years
Gasoline hybrid	5 years	20 years	10–15 years	35 years
Hydrogen fuel-cell hybrid	15 years	25 years	20 years	55 years

** More than one third of new vehicle production* † *More than one third of mileage driven*

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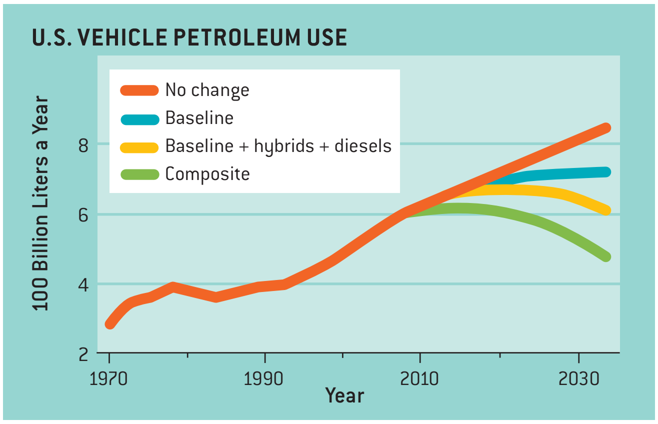

▲ Four scenarios project petroleum use over the next quarter of a century. "No change" assumes that fuel consumption per vehicle remains steady at 2008 levels. "Baseline" adds evolutionary improvements in technology, whereas "baseline + hybrids + diesels" assumes the gradual addition of gasoline-electric hybrid and diesel vehicles into the fleet, and "composite" adds to the mix a slowing in the growth of vehicles sold and vehicle-kilometers traveled.

ample), more efficient transmissions, and low-emission diesels with catalysts and particulate traps in the exhaust, and perhaps new approaches to how the fuel is combusted might be included as well. Hybrids, which combine a small gasoline engine and a battery-powered electric motor, are already on the road, and production volumes are growing. These vehicles use significantly less gasoline in urban driving, have lower benefits at highway speeds and cost a few thousand dollars extra to buy.

Researchers are exploring more radical propulsion systems and fuels, especially those that have the potential for low life-cycle carbon dioxide emissions. Several organizations are developing hydrogen-powered fuel cell vehicles in hybrid form with a battery and an electric motor. Such systems could increase vehicle efficiency by a factor of two, but much of that benefit is offset by the energy consumed and the emissions produced in making and distributing hydrogen. If the hydrogen can be produced through low-carbon-emitting processes and if a practical distribution system could be set up, it has low-greenhouse-emissions potential. But it would take technological breakthroughs and many decades before hydrogen-based transportation could become a reality and have widespread impact.

Hydrogen is, of course, an energy carrier rather than an energy source. Electricity is an alternative energy carrier with promise of producing energy without releasing carbon dioxide, and various research teams are looking at its use in transportation. The major challenge is coming up with a battery that can store enough energy for a reasonable driving range, at an acceptable cost. One technical barrier is the long battery recharging time. Those of us used to filling a 20-gallon tank in four minutes might have to wait for several hours to charge a battery. One way around the range limitation of electric vehicles is the plug-in hybrid, which has a small engine on-board to recharge the battery when needed. The energy used could thus be largely electricity and only part engine fuel. We do not yet know whether this plug-in hybrid technology will prove to be broadly attractive in the marketplace.

Beyond adopting improved propulsion systems, a switch to lighter-weight materials and different vehicle structures could reduce weight and improve fuel consumption without downsizing. Obviously, though, combining lighter materials and smaller vehicle size would produce an even greater effect. Maybe the way we use vehicles in the future will differ radically from our "general purpose vehicle" expectations of today. In the future, a car specifically designed for urban driving may make sense. Volkswagen, for example, has a small two-person concept car prototype that weighs 640 pounds (290 kilograms) and consumes one liter of gasoline per 100 kilometers (some 240 miles per gallon—existing average U.S. light-duty vehicles use 10 liters per 100 kilometers, or just under 25 miles per gallon). Some argue that downsizing reduces safety, but these issues can be minimized.

Promoting Change

BETTER TECHNOLOGY will undoubtedly improve fuel efficiency. In the developed world, markets may even adopt enough of these improvements to offset the expected increases in the number of vehicles. And gasoline prices will almost certainly rise over the next decade and beyond, prompting changes in the way consumers purchase and use their vehicles. But market forces alone are unlikely to curb our ever growing appetite for petroleum.

A coordinated package of fiscal and regulatory policies will need to come into play for fuel-reduction benefits to be realized from these future improvements. Effective policies would include a "feebate" scheme, in which customers pay an extra fee to buy big fuel-consumers but get a rebate if they buy small, fuel-efficient models. The feebate combines well with stricter Corporate Average Fuel Economy (CAFE) standards—in other words, with regulations that require automobile makers to produce products that consume less fuel. Adding higher fuel taxes to the package would further induce people to buy fuel-efficient models. And tax incentives could spur more rapid changes in the production facilities for new technologies. All these measures may be needed to keep us moving forward. SA

MORE TO EXPLORE

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JEN CHRISTIANSEN; SOURCE: M.I.T. LABORATORY FOR ENERGY AND ENVIRONMENT

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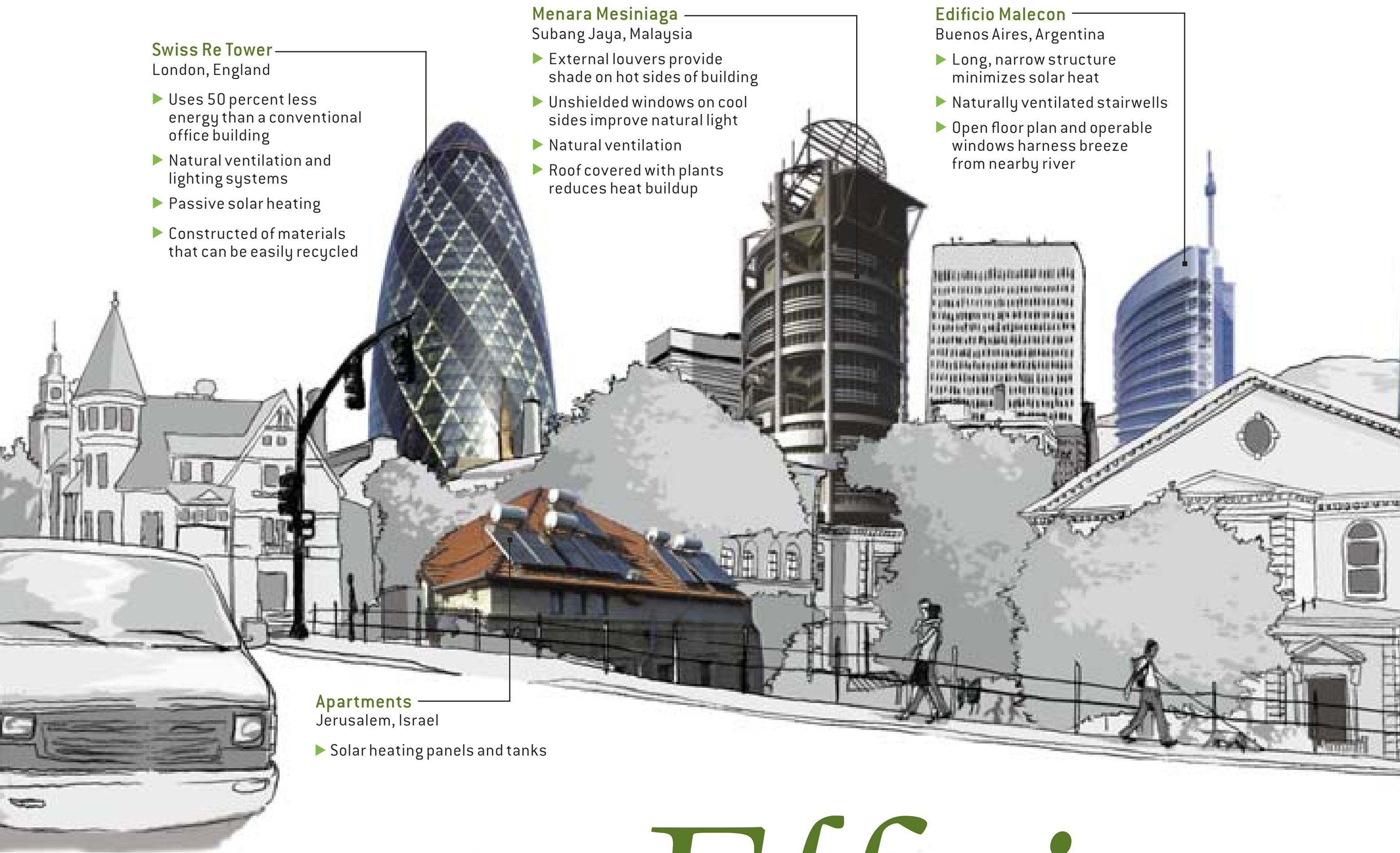

An Efficient

OVERVIEW

- Two thirds of all energy is lost during its conversion into forms used in human activities; most of this energy comes from carbon-emitting fossil fuels.
- The quickest, easiest way to reduce carbon emissions is to avoid as many of these losses as possible.
- Improving the energy efficiency of buildings, appliances and industrial processes offers impressive savings.

Wasting less energy is the quickest, least expensive way to stem carbon emissions **BY EBERHARD K. JOCHEM**

The huge potential of energy efficiency measures for mitigating the release of greenhouse gases into the atmosphere attracts little attention when placed alongside the more glamorous alternatives of nuclear, hydrogen or renewable energies. But developing a comprehensive efficiency strategy is the fastest and cheapest thing we can do to reduce carbon emissions. It can also be profitable and astonishingly effective, as two recent examples demonstrate.

From 2001 through 2005, Procter & Gamble's factory in Germany increased production by 45 percent, but the energy needed to run machines and to heat, cool and ventilate buildings rose by only 12 percent, and carbon emissions remained at the 2001 level. The major pillars supporting this success include highly efficient illumination, compressed-air systems, new designs for heating and air conditioning, funneling heat losses from compressors into heating buildings, and detailed energy measurement and billing.

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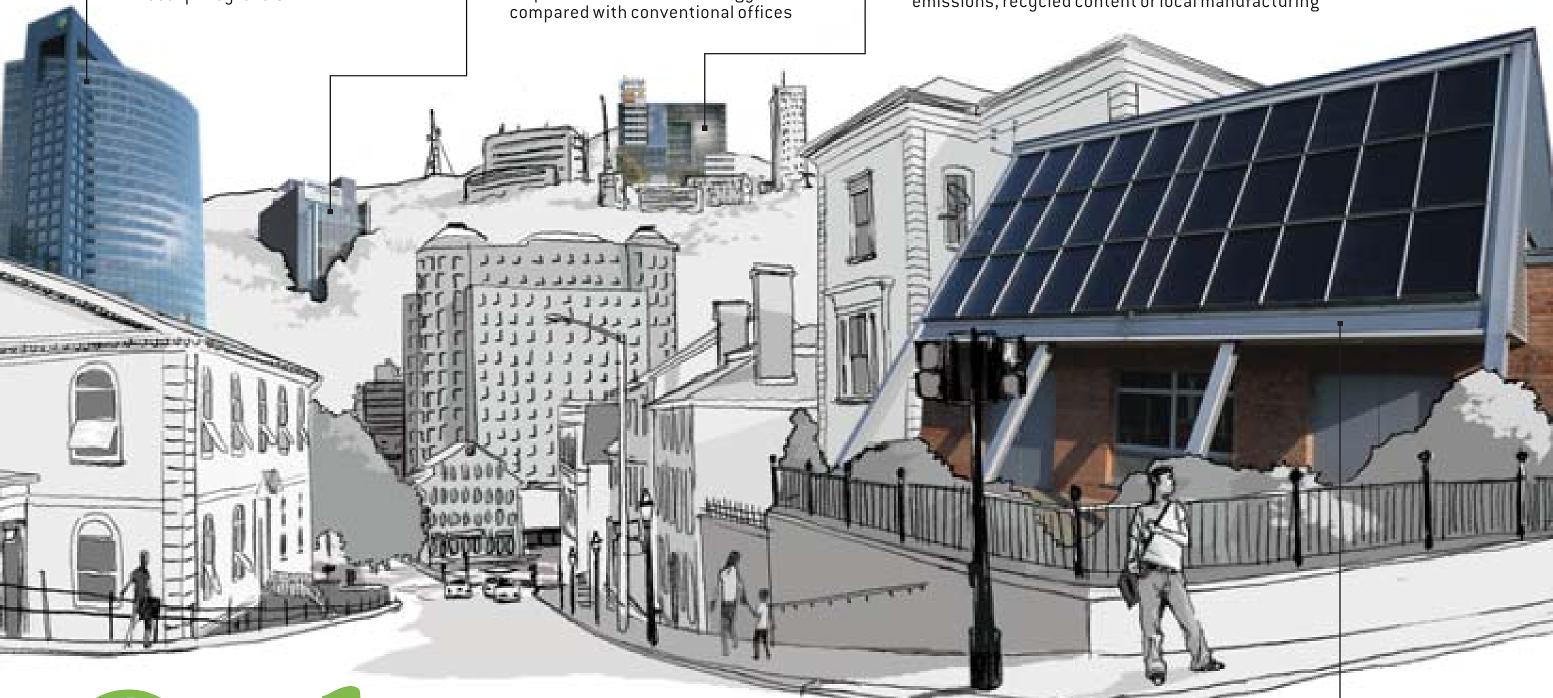

Solution

In some 4,000 houses and buildings in Germany, Switzerland, Austria and Scandinavia, extensive insulation, highly efficient windows and energy-conscious design have led to enormous efficiency increases, enabling energy budgets for heating that are a sixth of the requirement for typical buildings in these countries.

Improved efficiencies can be realized all along the energy chain, from the conversion of primary energy (oil, for example) to energy carriers (such as electricity) and finally to useful energy (the heat in your toaster). The annual global primary energy demand is 447,000 petajoules (a petajoule is roughly 300 gigawatt-hours), 80 percent of which comes from carbon-emitting fossil fuels such as coal, oil and gas. After conversion these primary energy sources deliver roughly 300,000 petajoules of so-called final energy to customers in the form of electricity, gasoline, heating oil, jet fuel, and so on.

The next step, the conversion of electricity, gasoline, and the like to useful energy in engines, boilers and lightbulbs, causes further energy losses of 154,000 petajoules. Thus, at present almost 300,000 petajoules, or two thirds of the primary energy, are lost during the two stages of energy conversion. Furthermore, all useful energy is eventually dissipated as heat at various temperatures. Insulating buildings more effectively, changing industrial processes and driving lighter, more aerodynamic cars [see "Fueling Our Transportation Future," by John B. Heywood, on page 60] would reduce the demand for useful energy, thus substantially reducing energy wastage.

Given the challenges presented by climate change and the high increases expected in energy prices, the losses that occur

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THE AUTHOR

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all along the energy chain can also be viewed as opportunities—and efficiency is one of the most important. New technologies and know-how must replace the present intensive use of energy and materials.

Room for Improvement

BECAUSE CONSERVATION MEASURES, whether incorporated into next year's car design or a new type of power plant, can have a dramatic impact on energy consumption, they also have an enormous effect on overall carbon emissions. In this mix, buildings and houses, which are notoriously inefficient in many countries today, offer the greatest potential for saving energy. In countries belonging to the Organization for Economic Cooperation and Development (OECD) and in the megacities of emerging countries, buildings contribute more than one third of total energy-related greenhouse gas emissions.

Little heralded but impressive advances have already been made, often in the form of efficiency improvements that are invisible to the consumer. Beginning with the energy crisis in the 1970s, air conditioners in the U.S. were redesigned to use less power with little loss in cooling capacity and new U.S. building codes required more insulation and double-paned windows. New refrigerators use only one quarter of the power of earlier models. (With approximately 150 million refrigerators and freezers in the U.S., the difference in consumption between 1974 efficiency levels and 2001 levels is equivalent to avoiding the generation of 40 gigawatts at power plants.) Changing to compact fluorescent lightbulbs yields an instant reduction in power demand; these bulbs provide as much light as regular incandescent bulbs, last 10 times longer and use just one fourth to one fifth the energy.

65 percent of primary energy—that in the natural resources we harness for power—is lost during conversion to the useful energy that makes our lives more comfortable

80 percent of primary energy comes from carbon-emitting fossil fuels

Almost **35 percent** of greenhouse gas emissions come from buildings

Despite these gains, the biggest steps remain to be taken. Many buildings were designed with the intention of minimizing construction costs rather than life-cycle cost, including energy use, or simply in ignorance of energy-saving considerations. Take roof overhangs, for example, which in warm climates traditionally measured a meter or so and which are rarely used today because of the added cost, although they would control heat buildup on walls and windows. One of the largest European manufacturers of prefabricated houses is now offering zero-net-energy houses: these well-insulated and intelligently designed structures with solar-thermal and photovoltaic collectors do not need commercial energy, and their total cost is similar to those of new houses built to conform to current building codes. Because buildings have a 50- to 100-year lifetime, efficiency retrofits are essential. But we need to coordinate changes in existing buildings thoughtfully to avoid replacing a single component, such as a furnace, while leaving in place leaky ducts and single-pane windows that waste much of the heat the new furnace produces.

One example highlights what might be done in industry: although some carpet manufacturers still dye their products at 100 to 140 degrees Celsius, others dye at room temperature using enzyme technology, reducing the energy demand by more than 90 percent.

The Importance of Policy

TO REALIZE THE FULL BENEFITS of efficiency, strong energy policies are essential. Among the underlying reasons for the crucial role of policy are the dearth of knowledge by manufacturers and the public about efficiency options, budgeting methods that do not take proper account of the ongoing benefits of long-lasting investments, and market imperfections such as external costs for carbon emissions and other costs of energy use. Energy policy set by governments has traditionally underestimated the benefits of efficiency. Of course, factors other than policy can drive changes in efficiency—higher energy prices, new technologies or cost competition, for instance. But policies—which include energy taxes, financial incentives, professional training, labeling, environmental legislation, greenhouse gas emissions trading and international coordination of regulations for traded products—can make an enormous difference. Furthermore, rapid growth in demand for energy services in emerging countries provides an opportunity to implement energy-efficient policies from the

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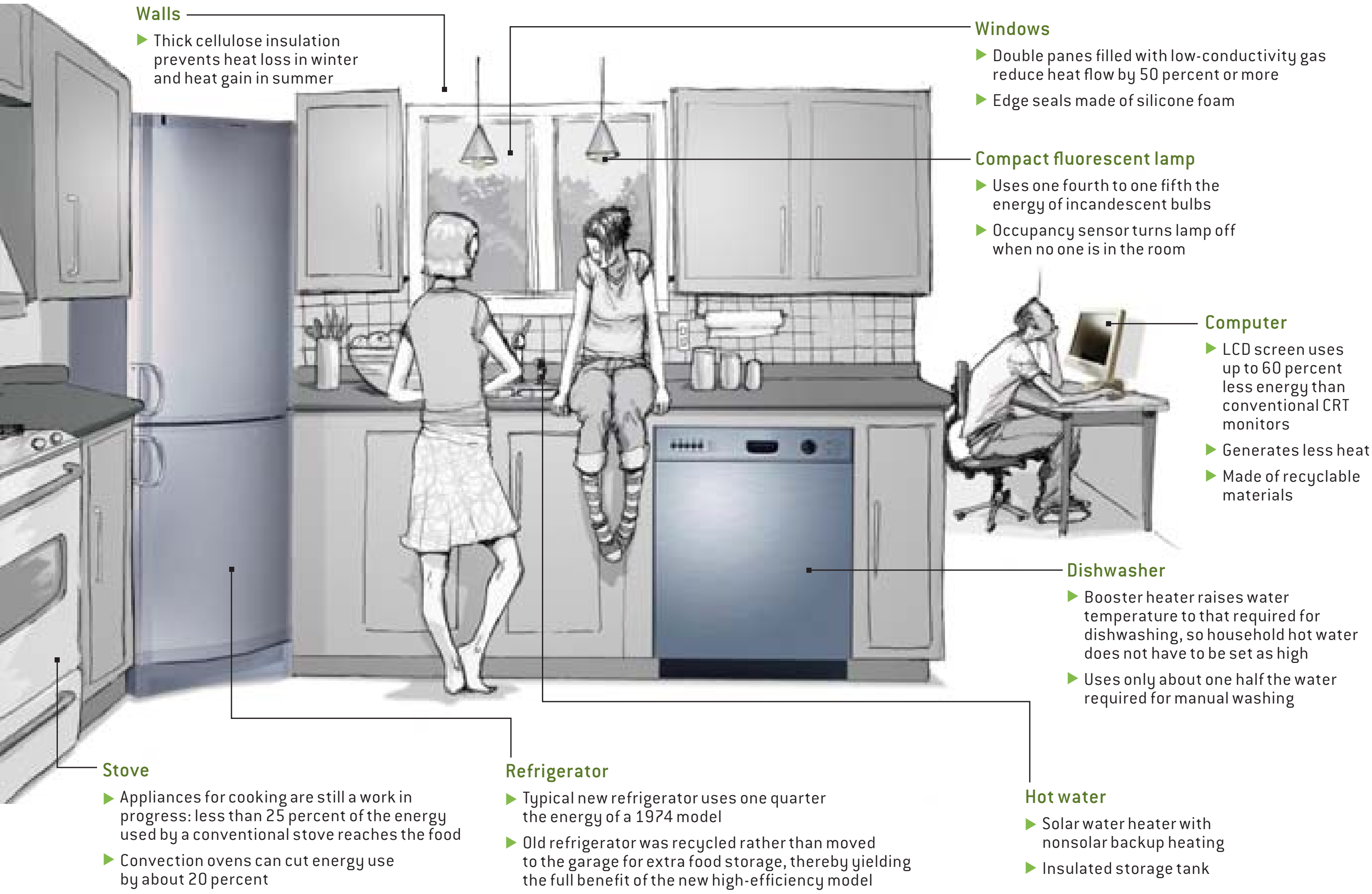

MATT VINCENT ILLUSTRATION; THE GREEN CULTURE/SOLARGOODS.COM (*refrigerator* and *dishwasher*); NEC CORPORATION OF AMERICA (*computer*); LUCY READING-IKKANDA (*lightbulbs*)

outset as infrastructure grows: programs to realize efficient solutions in buildings, transport systems and industry would give people the energy services they need without having to build as many power plants, refineries or gas pipelines.

Japan and the countries of the European Union have been more eager to reduce oil imports than the U.S. has and have encouraged productivity gains through energy taxes and other measures. But all OECD countries except Japan have so far failed to update appliance standards. Nor do gas and electric bills in OECD countries indicate how much energy is used for heating, say, as opposed to boiling water or which uses are the most energy-intensive—that is, where a reduction in usage would produce the greatest energy savings. In industry, compressed air, heat, cooling and electricity are often not billed by production line but expressed as an overhead cost.

Nevertheless, energy efficiency has a higher profile in Europe and Japan. A retrofitting project in Ludwigshafen, Germany, serves as just one example. Five years ago 500 dwellings were equipped to adhere to low-energy standards (about 30 kilowatt-hours per square meter per year), reducing the annual energy demand for heating those buildings by a factor of six. Before the retrofit, the dwellings were difficult to rent; now demand is three times greater than capacity.

Other similar projects abound. The Board of the Swiss Federal Institutes of Technology, for instance, has suggested a technological program aimed at what we call the 2,000-Watt Society—an annual primary energy use of 2,000 watts (or 65 gigajoules) per capita. Realizing this vision in industrial countries would reduce the per capita energy use and related carbon emissions by two thirds, despite a two-thirds increase in GDP, within the next 60 to 80 years. Swiss scientists, including myself, have been evaluating this plan since 2002, and we have concluded that the goal of the 2,000-watt per capita society is technically feasible for industrial countries in the second half of this century.

To some people, the term "energy efficiency" implies reduced comfort. But the concept of efficiency means that you get the same service—a comfortable room or convenient travel from home to work—using less energy. The EU, its member states and Japan have begun to tap the substantial—and profitable—potential of efficiency measures. To avoid the rising costs of energy supplies and the even costlier adaptations to climate change, efficiency must become a global activity. SA

MORE TO EXPLORE

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What to do

Cheap, plentiful coal is expected to fuel power plants for the foreseeable future, but can we keep it from devastating the environment?

BY DAVID G. HAWKINS, DANIEL A. LASHOF AND ROBERT H. WILLIAMS

OVERVIEW

- Coal is widely burned for power but produces large quantities of climate-changing carbon dioxide.
- Compared with conventional power plants, new gasification facilities can more effectively and affordably extract CO_2 so it can be safely stored underground.
- The world must begin implementing carbon capture and storage soon to stave off global warming.

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Burning coal sends nearly 10 billion metric tons of carbon dioxide into the atmosphere every year.

about Coal

More than most people realize, dealing with climate change means addressing the problems posed by emissions from coal-fired power plants. Unless humanity takes prompt action to strictly limit the amount of carbon dioxide (CO_2) released into the atmosphere when consuming coal to make electricity, we have little chance of gaining control over global warming.

Coal—the fuel that powered the Industrial Revolution—is a particularly worrisome source of energy, in part because burning it produces considerably more carbon dioxide per unit of electricity generated than burning either oil or natural gas does. In addition, coal is cheap and will remain abundant long after oil and natural gas have become very scarce. With coal plentiful and inexpensive, its use is burgeoning in the U.S. and elsewhere and is expected to continue rising in areas with abundant coal resources. Indeed, U.S. power providers are expected to build the equivalent of nearly 280 500-megawatt, coal-fired electricity plants between 2003 and 2030. Meanwhile China is already constructing the equivalent of one large coal-fueled power station a week. Over their roughly 60-year life spans, the new generating facilities in operation by 2030 could collectively introduce into the atmosphere about as much carbon dioxide as was released by all the

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coal burned since the dawn of the Industrial Revolution.

Coal's projected popularity is disturbing not only for those concerned about climate change but also for those worried about other aspects of the environment and about human health and safety. Coal's market price may be low, but the true costs of its extraction, processing and consumption are high. Coal use can lead to a range of harmful consequences, including decapitated mountains, air pollution from acidic and toxic emissions, and water fouled with coal wastes. Extraction also endangers and can kill miners. Together such effects make coal production and conversion to useful energy one of the most destructive activities on the planet [*see box on page 73*].

In keeping with *Scientific American*'s focus on climate concerns in this issue, we will concentrate below on methods that can help prevent CO_2 generated during coal conversion from reaching the atmosphere. It goes without saying that the environmental, safety and health effects of coal production and use must be reduced as well. Fortunately, affordable techniques for addressing CO_2 emissions and these other problems already exist, although the will to implement them quickly still lags significantly.

Geologic Storage Strategy

THE TECHNIQUES that power providers could apply to keep most of the carbon dioxide they produce from entering the air are collectively called CO_2 capture and storage (CCS) or geologic carbon sequestration. These procedures involve separating out much of the CO_2 that is created when coal is converted to useful energy and transporting it to sites where it can be stored deep underground in porous media—mainly in depleted oil or gas fields or in saline formations (permeable geologic strata filled with salty water) [see "Can We Bury Global Warming?" by Robert H. Socolow; Scientific American, July 2005].

All the technological components needed for CCS at coal conversion plants are commercially ready—having been proved in applications unrelated to climate change mitigation, although integrated systems have not yet been constructed at the necessary scales. Capture technologies have been deployed extensively throughout the world both in the manufacture of chemicals (such as fertilizer) and in the purification of natural gas supplies contaminated with carbon dioxide and hydrogen sulfide ("sour gas"). Industry has gained considerable experience with CO_2 storage in operations that purify natural gas (mainly in Canada) as well as with CO_2 injection to boost oil production (primarily in the U.S.). Enhanced oil recovery processes account for most of the CO_2 that has been sent into

> Affordable methods that prevent CO_2 from reaching the atmosphere exist; the will to implement them quickly lags.

underground reservoirs. Currently about 35 million metric tons are injected annually to coax more petroleum out of mature fields, accounting for about 4 percent of U.S. crude oil output.

Implementing CCS at coal-consuming plants is imperative if the carbon dioxide concentration in the atmosphere is to be kept at an acceptable level. The 1992 United Nations Framework Convention on Climate Change calls for stabilizing the atmospheric CO_2 concentration at a "safe" level, but it does not specify what the maximum value should be. The current view of many scientists is that atmospheric CO_2 levels must be kept below 450 parts per million by volume (ppmv) to avoid unacceptable climate changes. Realization of this aggressive goal requires that the power industry start commercial-scale CCS projects within the next few years and expand them rapidly thereafter. This stabilization benchmark cannot be realized by CCS alone but can plausibly be achieved if it is combined with other eco-friendly measures, such as wide improvements in energy efficiency and much expanded use of renewable energy sources.

The Intergovernmental Panel on Climate Change (IPCC) estimated in 2005 that it is highly probable that geologic media worldwide are capable of sequestering at least two trillion metric tons of CO_2—more than is likely to be produced by fossil-fuel-consuming plants during the 21st century. Society will want to be sure, however, that potential sequestration sites are evaluated carefully for their ability to retain CO_2 before they are allowed to operate. Two classes of risks are of concern: sudden escape and gradual leakage.

Rapid outflow of large amounts of CO_2 could be lethal to those in the vicinity. Dangerous sudden releases—such as that which occurred in 1986 at Lake Nyos in Cameroon, when CO_2 of volcanic origin asphyxiated 1,700 nearby villagers and thousands of cattle—are improbable for engineered CO_2 storage projects in carefully selected, deep porous geologic formations, according to the IPCC.

Gradual seepage of carbon dioxide into the air is also an issue, because over time it could defeat the goal of CCS. The 2005 IPCC report estimated that the fraction retained in appropriately selected and managed geologic reservoirs is very likely to exceed 99 percent over 100 years and likely to exceed 99 percent over 1,000 years. What remains to be demonstrated is whether in practice operators can routinely keep CO_2 leaks to levels that avoid unacceptable environmental and public health risks.

Technology Choices

DESIGN STUDIES indicate that existing power generation technologies could capture from 85 to 95 percent of the carbon in coal as CO_2, with the rest released to the atmosphere.

The coal conversion technologies that come to dominate will be those that

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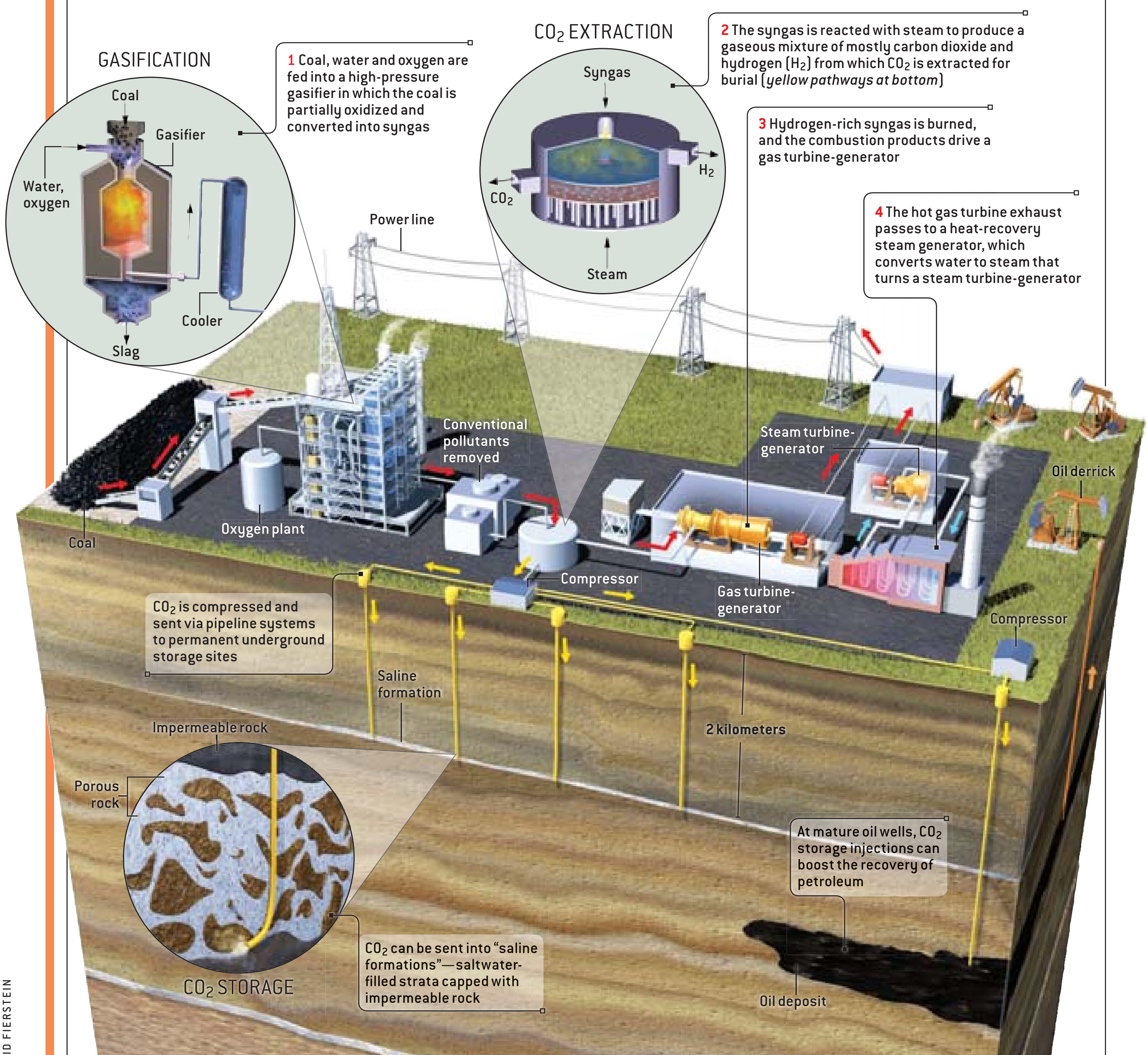
EXTRACTING AND STORING CARBON DIOXIDE

To slow climate change, the authors urge power providers to build integrated gasification combined cycle (IGCC) coal power plants with carbon dioxide capture and storage (CCS) capabilities (*below*) rather than conventional steam-electric facilities. Conventional coal plants burn the fuel to transform water into steam to turn a turbine-generator. If CCS technology were applied to a steam plant, CO_2 would be extracted from the flue exhaust. An IGCC plant, in contrast, employs a partial oxidation reaction using limited oxygen to convert the coal into a so-called synthesis gas, or syngas (mostly hydrogen and carbon monoxide). It is much easier and less costly to remove CO_2 from syngas than from the flue gases of a steam plant. The hydrogen-rich syngas remaining after CO_2 extraction is then burned to run both gas and steam turbine-generators. The world's first commercial IGCC project that will sequester CO_2 underground is being planned near Long Beach, Calif.



DAVID FIERSTEIN

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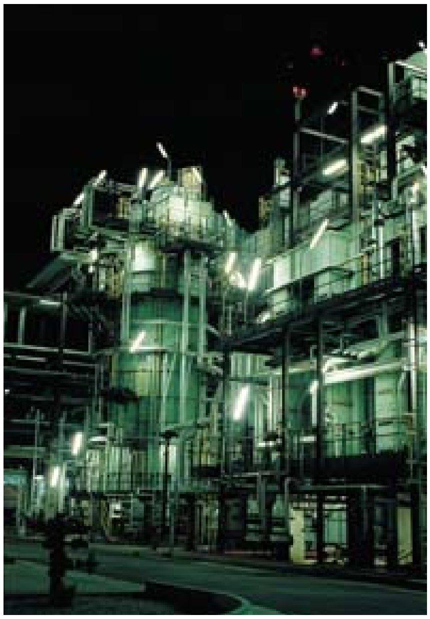
can meet the objectives of climate change mitigation at the least cost. Fundamentally different approaches to CCS would be pursued for power plants using the conventional pulverized-coal steam cycle and the newer integrated gasification combined cycle (IGCC). Although today's coal IGCC power (with CO_2 venting) is slightly more expensive than coal steam-electric power, it looks like IGCC is the most effective and least expensive option for CCS.

Standard plants burn coal in a boiler at atmospheric pressure. The heat generated in coal combustion transforms water into steam, which turns a steam turbine, whose mechanical energy is converted to electricity by a generator. In modern plants the gases produced by combustion (flue gases) then pass through devices that remove particulates and oxides of sulfur and nitrogen before being exhausted via smokestacks into the air.

Carbon dioxide could be extracted from the flue gases of such steam-electric plants after the removal of conventional pollutants. Because the flue gases contain substantial amounts of nitrogen (the result of burning coal in air, which is about 80 percent nitrogen), the carbon dioxide would be recovered at low concentration and pressure—which implies that the CO_2 would have to be removed from large volumes of gas using processes that are both energy-intensive and expensive. The captured CO_2 would then be compressed and piped to an appropriate storage site.

In an IGCC system coal is not burned but rather partially oxidized (reacted with limited quantities of oxygen from



▲ Commercial power plants using IGCC technology, such as this one in Italy, have been operating since 1994. Together they generate 3,600 megawatts of electricity.

an air separation plant, and with steam) at high pressure in a gasifier. The product of gasification is so-called synthesis gas, or syngas, which is composed mostly of carbon monoxide and hydrogen, undiluted with nitrogen. In current practice, IGCC operations remove most conventional pollutants from the syngas and then burn it to turn both gas and steam turbine-generators in what is called a combined cycle.

In an IGCC plant designed to capture CO_2, the syngas exiting the gasifier, after being cooled and cleaned of particles, would be reacted with steam to produce a gaseous mixture made up mainly of carbon dioxide and hydrogen. The CO_2 would then be extracted, dried, compressed and transported to a storage site. The remaining hydrogen-rich gas would be burned in a combined cycle plant to generate power [*see box on preceding page*].

Analyses indicate that carbon dioxide capture at IGCC plants consuming high-quality bituminous coals would entail significantly smaller energy and cost penalties and lower total generation costs than what could be achieved in conventional coal plants that captured and stored CO_2. Gasification systems recover CO_2 from a gaseous stream at high concentration and pressure, a feature that makes the process much easier than it would be in conventional steam facilities. (The extent of the benefits is less clear for lower-grade subbituminous coals and lignites, which have received much less study.) Precombustion removal of conventional pollutants, including mercury, makes it feasible to realize very low levels of emissions at much reduced costs and with much smaller energy penalties than with cleanup systems for flue gases in conventional plants.

Captured carbon dioxide can be transported by pipeline up to several hundred kilometers to suitable geologic storage sites and subsequent subterranean storage with the pressure produced during capture. Longer distances may, however, require recompression to compensate for friction losses during pipeline transfer.

Overall, pursuing CCS for coal power facilities requires the consumption of more coal to generate a kilowatt-hour of electricity than when CO_2 is vented—about 30 percent extra in the case of coal steam-electric plants and less than 20 percent more for IGCC plants. But overall coal use would not necessarily increase, because the higher price of coal-based electricity resulting from adding CCS equipment would dampen demand for coal-based electricity, making renewable energy sources and energy-efficient products more desirable to consumers.

The cost of CCS will depend on the type of power plant, the distance to the storage site, the properties of the storage

THE AUTHORS

DAVID G. HAWKINS, DANIEL A. LASHOF and ROBERT H. WILLIAMS have endeavored to help stave off climate change problems for decades. Hawkins is director of the Climate Center at the Natural Resources Defense Council (NRDC), where he has worked on air, energy and climate issues for 35 years. Hawkins serves on the boards of many bodies that advise government on environmental and energy subjects. Lashof is science director and deputy director of the NRDC's Climate Center, at which he has focused on national energy policy, climate science and solutions to global warming since 1989. Before arriving at the NRDC, Lashof developed policy options for stabilizing global climate at the U.S. Environmental Protection Agency. Williams is a senior research scientist at Princeton University, which he joined in 1975. At the university's Princeton Environmental Institute, he heads the Energy Systems/Policy Analysis Group and the Carbon Capture Group under the institute's Carbon Mitigation Initiative (which is supported by BP and Ford).

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reservoir and the availability of opportunities (such as enhanced oil recovery) for selling the captured CO_2. A recent study co-authored by one of us (Williams) estimated the incremental electric generation costs of two alternative CCS options for coal IGCC plants under typical production, transport and storage conditions. For CO_2 sequestration in a saline formation 100 kilometers from a power plant, the study calculated that the incremental cost of CCS would be 1.9 cents per kilowatt-hour (beyond the generation cost of 4.7 cents per kilowatt-hour for a coal IGCC plant that vents CO_2—a 40 percent premium). For CCS pursued in conjunction with enhanced oil recovery at a distance of 100 kilometers from the conversion plant, the analysis finds no increase in net generation cost would occur as long as the oil price is at least $35 per barrel, which is much lower than current prices.

CCS Now or Later?

MANY ELECTRICITY producers in the industrial world recognize that environmental concerns will at some point force them to implement CCS if they are to continue to employ coal. But rather than building plants that actually capture and store carbon dioxide, most plan to construct conventional steam facilities they claim will be "CO_2 capture ready"—convertible when CCS is mandated.

Power providers often defend those decisions by noting that the U.S. and most other countries with coal-intensive energy economies have not yet instituted policies for climate change mitigation that would make CCS cost-effective for uses not associated with enhanced oil recovery. Absent revenues from sales to oil field operators, applying CCS to new coal plants using current technology would be the least-cost path only if the cost of emitting CO_2 were at least $25 to $30 per metric ton. Many current policy proposals for climate change mitigation in the U.S. envision significantly lower cost penalties to power providers for releasing CO_2 (or similarly, payments for CO_2 emissions-reduction credits).

Yet delaying CCS at coal power plants until economy-wide carbon dioxide control costs are greater than CCS costs is shortsighted. For several reasons, the coal and power industries and

COAL'S TOLL

Despite the current popularity of the term "clean coal," coal is, in fact, dirty. Although carbon capture and storage could prevent much carbon dioxide from entering the atmosphere, coal production and consumption is still one of the most destructive industrial processes. As long as the world consumes coal, more must be done to mitigate the harm it causes.

MINING DANGERS

Coal mining is among the most dangerous occupations. Official reports for 2005 indicate that roughly 6,000 people died (16 a day) in China from coal mine floods, cave-ins, fires and explosions. Unofficial estimates are closer to 10,000. Some 600,000 Chinese coal miners suffer from black lung disease.

The U.S. has better safety practices than China and achieved an all-time low of 22 domestic fatalities in 2005. U.S. mines are far from perfect, however, as evidenced by a series of fatalities in early 2006.

ENVIRONMENTAL EFFECTS

Conventional coal mining, processing and transportation practices scar the landscape and pollute the water, which harms people and ecosystems. The most destructive mining techniques clear forests and blast away mountaintops. The "overburden" removed when a coal seam is uncovered is typically dumped into nearby valleys, where it often buries rivers and streams. Strip-mining operations rip apart ecosystems and reshape the landscape. Although regulations require land reclamation in principle, it is often left incomplete. As forests are replaced with nonnative grasslands, soils become compacted and streams contaminated.

Underground mining can cause serious problems on the surface. Mines collapse and cause land subsidence, damaging homes and roads. Acidic mine drainage caused by sulfur compounds leaching from coal waste into surface waters has tainted thousands of streams. The acid leachate releases heavy metals that foul groundwater.

▲ Acid runoff from a Pennsylvania coal mine stains this creek bed orange.

RICK SMITH *AP Photo*

TOXIC EMISSIONS

Coal-fired power plants account for more than two thirds of sulfur dioxide and about one fifth of nitrogen oxide emissions in the U.S. Sulfur dioxide reacts in the atmosphere to form sulfate particles, which in addition to causing acid rain, contribute to fine particulate pollution, a contaminant linked to thousands of premature deaths from lung disease nationwide. Nitrogen oxides combine with hydrocarbons to form smog-causing ground-level ozone.

Coal-burning plants also emit approximately 48 metric tons of mercury a year in America. This highly toxic element persists in the ecosystem. After transforming into methyl mercury, it accumulates in the tissues of fishes. Ingested mercury is particularly detrimental to fetuses and young infants exposed during periods of rapid brain growth, causing developmental and neurological damage.

—D.G.H., D.A.L. and R.H.W.

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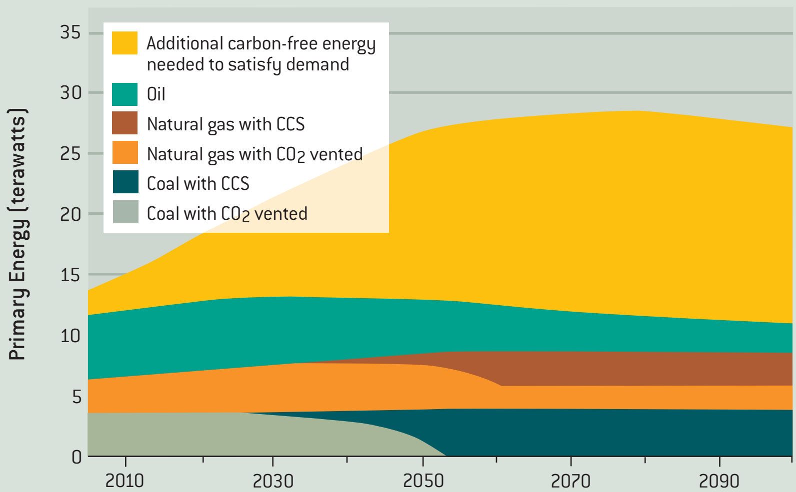
THE PATH TO CO_2 MITIGATION

Our calculations indicate that a prompt commitment to carbon capture and storage (CCS) would make it possible to meet global energy demands while limiting the atmospheric carbon dioxide concentration to 450 parts per million by volume (ppmv). This goal could be attained if, by midcentury, sequestration is applied for all coal use and about a quarter of natural gas use, while energy efficiency increases rapidly and carbon-free energy sources expand sevenfold. Under these conditions, overall fossil-fuel consumption could expand modestly from today: by midcentury, coal use could be somewhat higher than at present, oil use would be down by a fifth and natural gas use would expand by half.

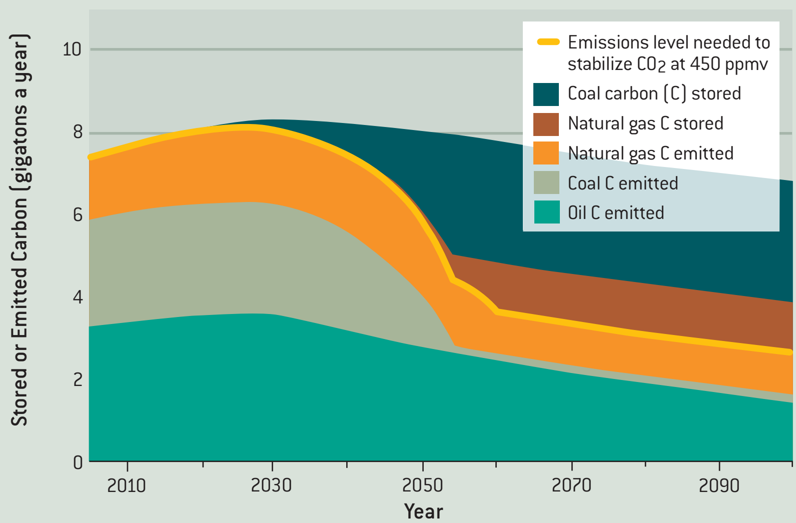
To realize this pathway, growth rates for fossil-fuel use would have to be reduced now, and CCS must begin for coal early in the next decade and for natural gas early in the next quarter of a century. The top graph below depicts the energy provided by the various sources if this mitigation path were followed. The bottom graph shows total quantities of carbon extracted from the earth (emissions plus storage).

—D.G.H., D.A.L. and R.H.W.

FOSSIL AND CARBON-FREE ENERGY MIX FOR CO_2 STABILIZATION



FATE OF CARBON FROM FOSSIL ENERGY SYSTEMS



society would ultimately benefit if deployment of plants fitted with CCS equipment were begun now.

First, the fastest way to reduce CCS costs is via "learning by doing"—the accumulation of experience in building and running such plants. The faster the understanding is accumulated, the quicker the know-how with the new technology will grow, and the more rapidly the costs will drop.

Second, installing CCS equipment as soon as possible should save money in the long run. Most power stations currently under construction will still be operating decades from now, when it is likely that CCS efforts will be obligatory. Retrofitting generating facilities for CCS is inherently more expensive than deploying CCS in new plants. Moreover, in the absence of CO_2 emission limits, familiar conventional coal steam-electric technologies will tend to be favored for most new plant construction over newer gasification technologies, for which CCS is more cost-effective.

Finally, rapid implementation would allow for continued use of fossil fuels in the near term (until more environmentally friendly sources become prevalent) without pushing atmospheric carbon dioxide beyond tolerable levels. Our studies indicate that it is feasible to stabilize atmospheric CO_2 levels at 450 ppmv over the next half a century if coal-based energy is completely decarbonized and other measures described in the box at the left are implemented. This effort would involve decarbonizing 36 gigawatts of new coal generating capacity by 2020 (corresponding to 7 percent of the new coal capacity expected to be built worldwide during the decade beginning in 2011 under business-as-usual conditions). In the 35 years after 2020, CO_2 capture would need to rise at an average rate of about 12 percent a year. Such a sustained pace is high compared with typical market growth rates for energy but is not unprecedented. It is much less than the expansion rate for nuclear generating capacity in its heyday—1956 to 1980—during which global capacity rose at an average rate of 40 percent annually. Further, the

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expansion rates for both wind and solar photovoltaic power capacities worldwide have hovered around 30 percent a year since the early 1990s. In all three cases, such growth would not have been practical without public policy measures to support them.

Our calculations indicate that the costs of CCS deployment would be manageable as well. Using conservative assumptions—such as that technology will not improve over time—we estimate that the present worth of the cost of capturing and storing all CO_2 produced by coal-based electricity generation plants during the next 200 years will be \$1.8 trillion (in 2002 dollars). That might seem like a high price tag, but it is equivalent to just 0.07 percent of the current value of gross world product over the same interval. Thus, it is plausible that a rapid decarbonization path for coal is both physically and economically feasible, although detailed regional analyses are needed to confirm this conclusion.

Policy Push Is Needed

THOSE GOOD REASONS for commencing concerted CCS efforts soon will probably not move the industry unless it is also prodded by new public policies. Such initiatives would be part of a broader drive to control carbon dioxide emissions from all sources.

In the U.S., a national program to limit CO_2 emissions must be enacted soon to introduce the government regulations and market incentives necessary to shift investment to the least-polluting energy technologies promptly and on a wide scale. Leaders in the American business and policy communities increasingly agree that quantifiable and enforceable restrictions on global warming emissions are imperative and inevitable. To ensure that power companies put into practice the reductions in a cost-effective fashion, a market for trading CO_2 emissions credits should be created—one similar to that for the sulfur emissions that cause acid rain. In such a plan, organizations that intend to exceed designated emission limits may buy credits from others that are able to stay below these values.

Enhancing energy efficiency efforts and raising renewable energy production are critical to achieving carbon dioxide limits at the lowest possible cost. A portion of the emission allowances created by a carbon cap-and-trade program should be allocated to the establishment of a fund to help overcome institutional barriers and technical risks that obstruct widespread deployment of otherwise cost-effective CO_2 mitigation technologies.

> Delaying carbon capture and storage at coal power plants is shortsighted.

Even if a carbon dioxide cap-and-trade program were enacted in the next few years the economic value of CO_2 emissions reduction may not be enough initially to convince power providers to invest in power systems with CCS. To avoid the construction of another generation of conventional coal plants, it is essential that the federal government establish incentives that promote CCS.

One approach would be to insist that an increasing share of total coal-based electricity generation comes from facilities that meet a low CO_2 emissions standard—perhaps a maximum of 30 grams of carbon per kilowatt-hour (an achievable goal using today's coal CCS technologies). Such a goal might be achieved by obliging electricity producers that use coal to include a growing fraction of decarbonized coal power in their supply portfolios. Each covered electricity producer could either generate the required amount of decarbonized coal power or purchase decarbonized-generation credits. This system would share the incremental costs of CCS for coal power among all U.S. coal-based electricity producers and consumers.

If the surge of conventional coal-fired power plants currently on drawing boards is built as planned, atmospheric carbon dioxide levels will almost certainly exceed 450 ppmv. We can meet global energy needs while still stabilizing CO_2 at 450 ppmv, however, through a combination of improved efficiency in energy use, greater reliance on renewable energy resources and, for the new coal investments that are made, the installation of CO_2 capture and geologic storage technologies. Even though there is no such thing as "clean coal," more can and must be done to reduce the dangers and environmental degradations associated with coal production and use. An integrated low-carbon energy strategy that incorporates CO_2 capture and storage can reconcile substantial use of coal in the coming decades with the imperative to prevent catastrophic changes to the earth's climate. SA

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The Nuclear

A threefold expansion of nuclear power could contribute significantly to staving off climate change by avoiding one billion to two billion tons of carbon emissions annually

BY JOHN M. DEUTCH AND ERNEST J. MONIZ


KENN BROWN

Nuclear power supplies a sixth of the world's electricity. Along with hydropower (which supplies slightly more than a sixth), it is the major source of "carbon-free" energy today. The technology suffered growing pains, seared into the public's mind by the Chernobyl and Three Mile Island accidents, but plants have demonstrated remarkable reliability and efficiency recently. The world's ample supply of uranium could fuel a much larger fleet of reactors than exists today throughout their 40- to 50-year life span.

With growing worries about global warming and the associated likelihood that greenhouse gas emissions will be regulated in some fashion, it is not surprising that governments and power providers in the U.S. and elsewhere are increasingly considering building a substantial number of additional nuclear power plants. The fossil-fuel alternatives have their drawbacks. Natural gas is attractive in a carbon-constrained world because it has lower carbon

▶ Governments and utilities are considering a new wave of nuclear power plant construction to help meet rising electricity demand.

OVERVIEW

- Global electricity consumption is projected to increase 160 percent by 2050.
- Building hundreds of nuclear power plants will help meet that need without large new emissions of carbon dioxide.
- This scenario requires economical new plants, a plan for waste storage and prevention of nuclear weapons proliferation.

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Option

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content relative to other fossil fuels and because advanced power plants have low capital costs. But the cost of the electricity produced is very sensitive to natural gas prices, which have become much higher and more volatile in recent years. In contrast, coal prices are relatively low and stable, but coal is the most carbon-intensive source of electricity. The capture and sequestration of carbon dioxide, which will add significantly to the cost, must be demonstrated and introduced on a large scale if coal-powered electricity is to expand significantly without emitting unacceptable quantities of carbon into the atmosphere. These concerns raise doubts about new investments in gas- or coal-powered plants.

All of which points to a possible nuclear revival. And indeed, more than 20,000 megawatts of nuclear capacity have come online globally since 2000, mostly in the Far East. Yet despite the evident interest among major nuclear operators, no firm orders have been placed in the U.S. Key impediments to new nuclear construction are high capital costs and the uncertainty surrounding nuclear waste management. In addition, global expansion of nuclear power has raised concerns that nuclear weapons ambitions in certain countries may inadvertently be advanced.

In 2003 we co-chaired a major Massachusetts Institute of Technology study, *The Future of Nuclear Power,* that analyzed what would be required to retain the nuclear option. That study described a scenario whereby worldwide nuclear power generation could triple to one million megawatts by the year 2050, saving the globe from emissions of between 0.8 billion and 1.8 billion tons of carbon a year, depending on whether gas- or coal-powered plants were displaced. At this scale, nuclear power would significantly contribute to the stabilization of greenhouse gas emissions, which requires about seven billion tons of carbon to be averted annually by 2050 [see "A Plan to Keep Carbon in Check," by Robert H. Socolow and Stephen W. Pacala, on page 50].

The Fuel Cycle

IF NUCLEAR POWER is to expand by such an extent, what kind of nuclear plants should be built? A chief consideration is the fuel cycle, which can be either open or closed. In an open fuel cycle, also known as a once-through cycle, the uranium is "burned" once in a reactor, and spent fuel is stored in geologic repositories. The spent fuel includes plutonium that could be chemically extracted and turned into fuel for use in another nuclear plant. Doing that results in a closed fuel cycle, which some people advocate [see "Smarter Use of Nuclear Waste," by William H. Hannum, Gerald E. Marsh and George S. Stanford; SCIENTIFIC AMERICAN, December 2005].

Some countries, most notably France, currently use a closed fuel cycle in which plutonium is separated from the spent fuel and a mixture of plutonium and uranium oxides is subsequently burned again. A longer-term option could involve recycling all the transuranics (plutonium is one example of a transuranic element), perhaps in a so-called fast reactor. In this approach, nearly all the very long lived components of the waste are eliminated, thereby transforming the nuclear waste debate. Substantial research and development is needed, however, to work through daunting technical and economic challenges to making this scheme work.

Recycling waste for reuse in a closed cycle might seem like a no-brainer: less raw material is used for the same total power output, and the problem of long-term storage of waste is alleviated because a smaller amount of radioactive material must be stored for many thousands of years. Nevertheless, we believe that an open cycle is to be preferred over the next several decades. First, the recycled fuel is more expensive than the original uranium. Second, there appears to be ample uranium at reasonable cost to sustain the tripling in global nuclear power generation that we envisage with a once-through fuel cycle for the entire lifetime of the nuclear fleet (about 40 to 50 years for each plant). Third, the environmental benefit for long-term waste storage is offset by near-term risks to the environment from the complex and highly dangerous reprocessing and fuel-fabrication operations. Finally, the reprocessing that occurs in a closed fuel cycle produces plutonium that can be diverted for use in nuclear weapons.

The type of reactor that will continue to dominate for at least two decades, probably longer, is the light-water reactor, which uses ordinary water (as opposed to heavy water, containing deuterium) as the coolant and moderator. The vast majority of plants in operation in the world today are of this type, making it a mature, well-understood technology.

Reactor designs are divided into generations. The earliest prototype reactors, built in the 1950s and early 1960s, were often one of a kind. Generation II reactors, in contrast, were commercial designs built in large numbers from the late 1960s to the early 1990s. Generation III reactors incorporate design improvements such as better fuel technology and passive safety, meaning that in the case of an accident the reactor shuts itself down without requiring the operators to intervene. The first generation III reactor was built in Japan in 1996. Generation IV reactors are new designs that are currently being researched, such as pebble-bed reactors and lead-cooled fast reactors [see "Next-Generation Nuclear Power," by James A.

More than 20,000 megawatts of nuclear capacity have come online globally since 2000.

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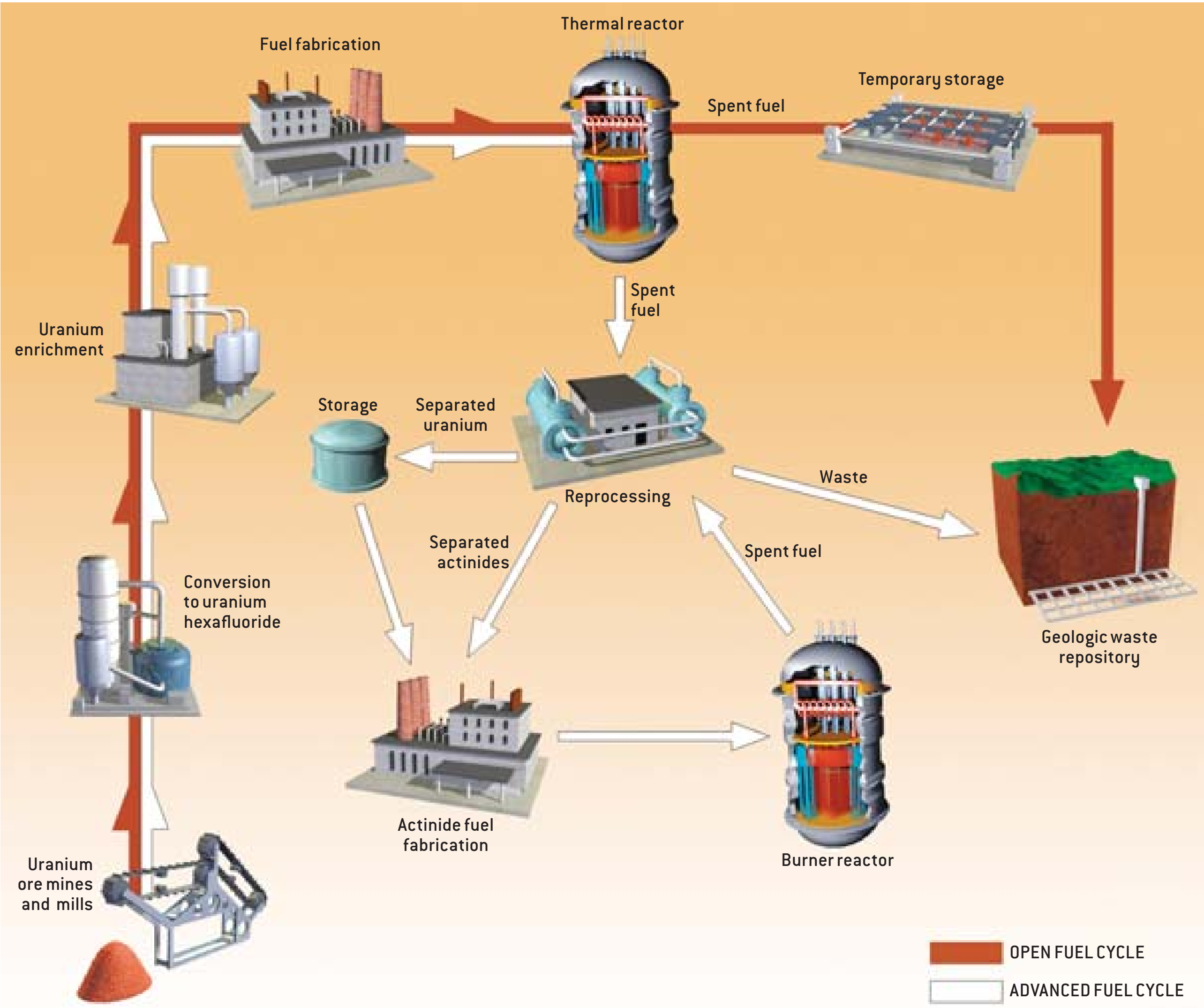
PREFERRED FUEL CYCLES

The authors prefer an open fuel cycle for the next several decades: the uranium is burned once in a thermal reactor, and the spent fuel is stored in a waste repository (*red path*). Some countries currently use a closed cycle in which plutonium is extracted from spent fuel and mixed with uranium for reuse in a thermal reactor (*not shown*).

An advanced closed cycle (*white path*) might become feasible and preferred in the distant future: plutonium and other elements (actinides) and perhaps the uranium in spent fuel would be reprocessed and used in special burner reactors, dramatically reducing the quantity of waste requiring long-term storage.



DON FOLEY

Lake, Ralph G. Bennett and John F. Kotek; Scientific American, January 2002]. In addition, generation III+ reactors are designs similar to generation III but with the advanced features further evolved. With the possible exception of high-temperature gas reactors (the pebble bed is one example), generation IV reactors are several decades away from being candidates for significant commercial deployment. To evaluate our scenario through to 2050, we envisaged the building of generation III+ light-water reactors.

The pebble-bed modular reactor introduces the interesting prospect of modular nuclear plants. Instead of building a massive 1,000-megawatt plant, modules each producing around 100 megawatts can be built. This approach may be particularly attractive, both in developing countries and in deregulated industrial countries, because of the much lower capital costs involved. The traditional large plants do have the advantage of economy of scale, most likely resulting in lower cost per kilowatt of capacity, but this edge could be challenged if efficient factory-style production of large numbers of modules could be implemented. South Africa is scheduled to begin construction of a 110-megawatt demonstration pebble-bed plant in 2007, to be completed by 2011, with commercial modules of about 165 megawatts planned for 2013. The hope is to sell modules internationally, in particular throughout Africa.

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Reducing Costs

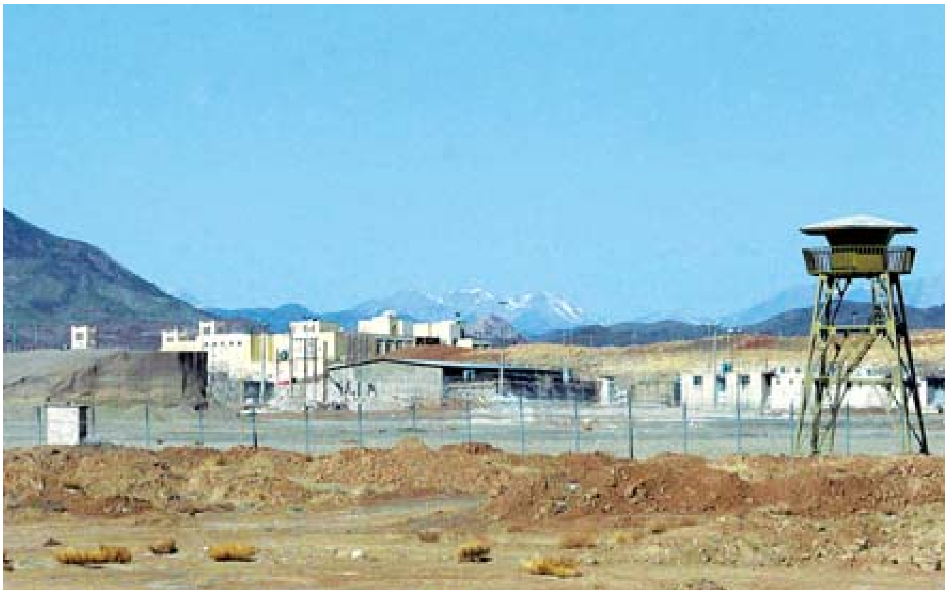
BASED ON PREVIOUS EXPERIENCE, electricity from new nuclear power plants is currently more expensive than that from new coal- or gas-powered plants. The 2003 M.I.T. study estimated that new light-water reactors would produce electricity at a cost of 6.7 cents per kilowatt-hour. That figure includes all the costs of a plant, spread over its life span, and includes items such as an acceptable return to investors. In comparison, under equivalent assumptions we estimated that a new coal plant would produce electricity at a cost of 4.2 cents per kilowatt-hour. For a new gas-powered plant, the cost is very sensitive to the price of natural gas and would be about 5.8 cents per kilowatt-hour for today's high gas prices (about $7 per million Btu).

Some people will be skeptical about how well the cost of nuclear power can be estimated, given past overoptimism, going back to claims in the early days that nuclear power would be "too cheap to meter." But the M.I.T. analysis is grounded in past experience and actual performance of existing plants, not in promises from the nuclear industry. Some might also question the uncertainties inherent in such cost projections. The important point is that the estimates place the three alternatives—nuclear, coal and gas—on a level playing field, and there is no reason to expect unanticipated contingencies to favor one over the other. Furthermore, when utilities are deciding what kind of power plant to build, they will base their decisions on such estimates.

Several steps could reduce the cost of the nuclear option below our baseline figure of 6.7 cents per kilowatt-hour. A 25 percent reduction in construction expenses would bring the cost of electricity down to 5.5 cents per kilowatt-hour. Reducing the construction time of a plant from five to four years and improvements in operation and maintenance can shave off a further 0.4 cent per kilowatt-hour. How any plant is financed can depend dramatically on what regulations govern the plant site. Reducing the cost of capital for a nuclear plant to be the same as for a gas or coal plant would close the gap with coal (4.2 cents per kilowatt-hour). All these reductions in the cost of nuclear power are plausible—particularly if the industry builds a large number of just a few standardized designs—but not yet proved.

Nuclear power becomes distinctly favored economically if carbon emissions are priced [*see box on opposite page*]. We will refer to this as a carbon tax, but the pricing mechanism need not be in the form of a tax. Europe has a system in which permits to emit carbon are traded on an open market. In early 2006 permits were selling for more than $100 per tonne of carbon emitted (or $27 per tonne of carbon dioxide), although recently their price has fallen to about half that. (A metric unit, one tonne is equal to 1.1 U.S. tons.) A tax of only $50 per tonne of carbon raises coal-powered electricity to 5.4 cents per kilowatt-hour. At $200 per tonne of carbon, coal reaches a whopping 9.0 cents per kilowatt-hour. Gas fares much better than coal, increasing to 7.9 cents per kilowatt-hour under a $200 tax. Fossil-fuel plants could avoid the putative carbon tax by capturing and sequestering the carbon, but the cost of doing that contributes in the same way that a tax would [see "Can We Bury Global Warming?" by Robert H. Socolow; SCIENTIFIC AMERICAN, July 2005].

Because it is many years since construction of a nuclear plant was embarked on in the U.S., the companies that build the first few new plants will face extra expenses that subsequent operators will not have to bear, along with additional risk in working through a new licensing process. To help over-



▲ Activities at this uranium enrichment plant in Natanz, Iran, have been a focus of concern in recent years because the facility could be used to make weapons-grade uranium. An international agreement whereby "user" countries lease fuel from "supplier" countries such as the U.S. instead of building their own enrichment plants would help alleviate the threat of nuclear weapons proliferation.

GETTY IMAGES

THE AUTHORS

JOHN M. DEUTCH and ERNEST J. MONIZ are professors at the Massachusetts Institute of Technology and co-chaired the 2003 interdisciplinary M.I.T. study entitled *The Future of Nuclear Power.* They have held several government positions. Deutch was director of energy research and undersecretary of energy (1977–1980) and later deputy secretary of defense (1994–1995) and director of central intelligence (1994–1996). Moniz was associate director for science in the Office of Science and Technology Policy (1995–1997) and undersecretary of energy (1997–2001). They are currently co-chairing an M.I.T. study on the future of coal.

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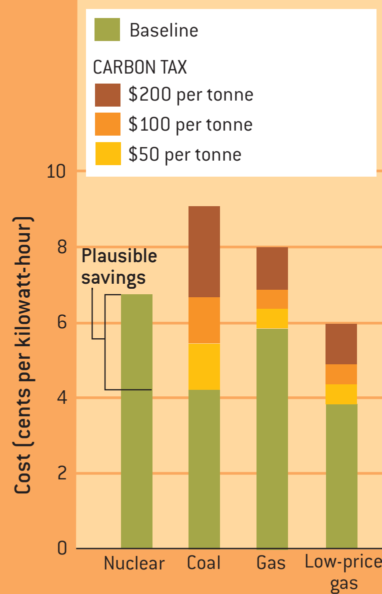
INTO THE FUTURE

The global demand for electricity will increase substantially in the coming decades (*below*). To meet that demand, thousands of new power plants must be built. One of the most significant factors in determining what kind of facilities are built will be the estimated cost of the electricity produced (*right*). Nuclear plants will not be built in large numbers if they are not economically competitive with coal- and gas-powered plants. If nuclear plants can be made competitive, global nuclear power production might triple from 2000 to 2050, a scenario evaluated by an M.I.T. study (*bottom*).

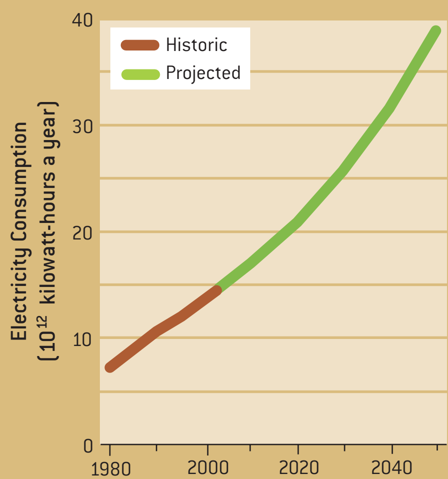
PAYING THE PIPER



The cost of electricity projected for newly built power plants depends on many factors. Taxes on carbon emissions could raise costs for coal and gas. Nuclear may be reduced by plausible but unproved cost-cutting steps.

ELECTRICITY CONSUMPTION

Global use of electricity is projected to increase 160 percent by 2050. The projection (*green*) uses United Nations population estimates and assumes that consumption per capita increases by about 1 percent annually in developed countries. Higher rates of increase are assumed for developing countries while they catch up to the developed world's usage levels.

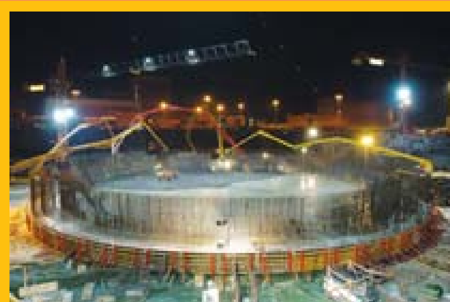


WHO WILL HAVE THE POWER?

The M.I.T. scenario projects that the U.S. will produce about a third of the one million megawatts of electricity that will be generated by nuclear power in 2050 and that the rest of the developed world will provide another third.

GENERATION CAPACITY, 2050

- U.S.
- Europe and Canada
- Developed East Asia
- Former Soviet Union
- China, India and Pakistan
- Indonesia, Brazil and Mexico
- Other developing countries



▲ Under construction: an advanced (generation III+) 1,600-megawatt nuclear power plant in Olkiluoto, Finland.

come that hurdle, the Energy Policy Act of 2005 included a number of important provisions, such as a tax credit of 1.8 cents per kilowatt-hour to new nuclear plants for their first eight years of operation. The credit, sometimes called a first-mover incentive, applies to the first 6,000 megawatts of new plants to come online. Several consortiums have formed to take advantage of the new incentives.

Waste Management

THE SECOND BIG OBSTACLE that a nuclear renaissance faces is the problem of waste management. No country in the world has yet implemented a system for permanently disposing of the spent fuel and other radioactive waste produced by nuclear power plants. The most widely favored approach is geologic disposal, in which waste is stored in chambers hundreds of meters underground. The goal is to prevent leakage of the waste for many millennia through a combination of engineered barriers (for example, the waste containers) and geologic ones (the natural rock structure where the chamber has been excavated and the favorable characteristics of the hydrogeologic basin). Decades of studies support the geologic disposal option. Scientists have a good understanding of the processes and events that could transport radionuclides from the repository to the biosphere. Despite this scientific confidence, the process

JEN CHRISTIANSEN; SOURCES: ENERGY INFORMATION ADMINISTRATION AND ERNEST J. MONIZ (*electricity consumption*); "THE FUTURE OF NUCLEAR POWER," BY STEPHEN ANSOLABEHERE ET AL., MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2003 (*cost of electricity and generation capacity*); AREVA (*photograph*)

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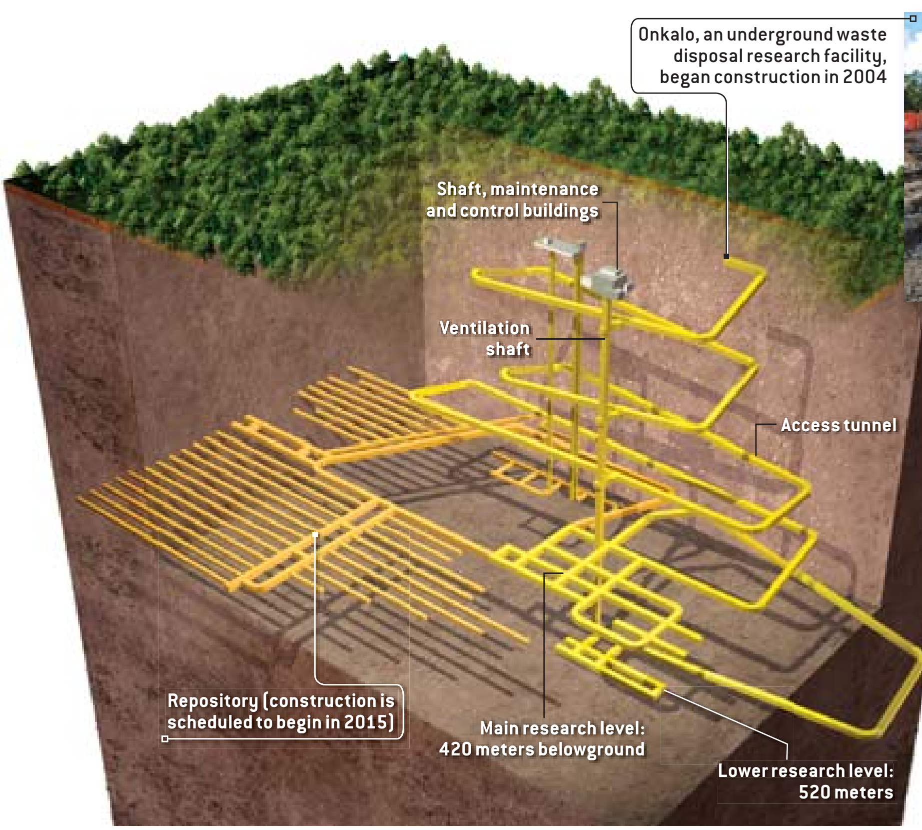
NUCLEAR WASTE DISPOSAL

Finland is moving ahead with a project to investigate underground disposal of nuclear waste at Olkiluoto. Under the plan, spent fuel rods will be encapsulated in large canisters made of an inner shell of iron for mechanical strength and a thick outer shell of copper to resist corrosion. The canisters will be placed in holes bored into the tunnel floors and surrounded by clay to prevent direct water flow to the canisters. The facility could begin accepting waste from Finland's four nuclear reactors in 2020.



Onkalo, an underground waste disposal research facility, began construction in 2004

Spent fuel will be placed in an iron canister (*left*) and sealed in a copper shell (*right*)

DON FOLEY; SOURCE: POSIVA; COURTESY OF POSIVA (*photographs*)

of approving a geologic site remains fraught with difficulties.

A prime case in point is the proposed facility at Yucca Mountain in Nevada, which has been under consideration for two decades. Recently the site was found to have considerably more water than anticipated. It remains uncertain whether the Nuclear Regulatory Commission (NRC) will license the site.

Delays in resolving waste management (even if it is approved, it is unlikely that Yucca Mountain will be accepting waste before 2015) may complicate efforts to construct new power plants. By law, the government was to begin moving spent fuel from reactor sites to a repository by 1998. Failure to do so has led to a need for increased local storage at many sites and associated unhappiness among neighbors, towns and states.

Perhaps the first country to build a permanent storage site for its high-level nuclear waste will be Finland. At Olkiluoto, the location of two nuclear reactors, excavation has begun on an underground research facility called Onkalo. Extending about half a kilometer underground, the Onkalo project will involve study of the rock structure and groundwater flows and will test the disposal technology in actual deep underground conditions. If all goes according to plan and the necessary government licenses are obtained, the first canisters of waste could be emplaced in 2020. By 2130 the repository would be complete, and the access routes would be filled and sealed. The money to pay for the facility has been levied on the price of Finnish nuclear power since the late 1970s.

To address the waste management problem in the U.S., the government should take title to the spent fuel stored at commercial reactor sites across the country and consolidate it at one or more federal interim storage sites until a permanent disposal facility is built. The waste can be temporarily stored safely and securely for an extended period. Such extended temporary storage, perhaps even for as long as 100 years, should be an integral part of the disposal strategy. Among other benefits, it would take the pressure off government and industry to come up with a hasty disposal solution.

Meanwhile the Department of Energy should not abandon Yucca Mountain. Instead it should reassess the suitability of the site under various conditions and modify the project's schedule as needed. If nuclear power expanded globally to one million megawatts, enough high-level waste and spent fuel would be generated in the open fuel cycle to fill a Yucca Mountain–size

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facility every three and a half years. In the court of public opinion, that fact is a significant disincentive to the expansion of nuclear power, yet it is a problem that can and must be solved.

The Threat of Proliferation

IN CONJUNCTION WITH the domestic program of waste management just outlined, the president should continue the diplomatic effort to create an international system of fuel supplier countries and user countries. Supplier countries such as the U.S., Russia, France and the U.K. would sell fresh fuel to user countries with smaller nuclear programs and commit to removing the spent fuel from them. In return, the user countries would forgo the construction of fuel-producing facilities. This arrangement would greatly alleviate the danger of nuclear weapons proliferation because the chief risks for proliferation involve not the nuclear power plants themselves but the fuel enrichment and reprocessing plants. The current situation with Iran's uranium enrichment program is a prime example. A scheme in which fuel is leased to users is a necessity in a world where nuclear power is to expand threefold, because such an expansion will inevitably involve the spread of nuclear power plants to some countries of proliferation concern.

A key to making the approach work is that producing fuel does not make economic sense for small nuclear power programs. This fact underlies the marketplace reality that the world is already divided into supplier and user countries. Instituting the supplier/user model is largely a matter, albeit not a simple one, of formalizing the current situation more permanently through new agreements that reinforce commercial realities.

Although the proposed regime is inherently attractive to user nations—they get an assured supply of cheap fuel and are relieved of the problem of dealing with waste materials—other incentives should also be put in place because the user states would be agreeing to go beyond the requirements of the treaty on the nonproliferation of nuclear weapons. For example, if a global system of tradable carbon credits were instituted, user nations adhering to the fuel-leasing rules could be granted credits for their new nuclear power plants.

Iran is the most obvious example today of a nation that the global community would rather see as a "user state" than as a producer of enriched uranium. But it is not the only difficult case. Another nation whose program must be addressed promptly is Brazil, where an enrichment facility is under construction supposedly to provide fuel for the country's two nuclear reactors. A consistent approach to countries such as Iran and Brazil will be needed if nuclear power is to be expanded globally without exacerbating proliferation concerns.

The Terawatt Future

A TERAWATT—one million megawatts—of "carbon-free" power is the scale needed to make a significant dent in projected carbon dioxide emissions at midcentury. In the terms used by Socolow and Pacala, that contribution would correspond to one to two of the seven required "stabilization wedges." Reaching a terawatt of nuclear power by 2050 is certainly challenging, requiring deployment of about 2,000 megawatts a month. A capital investment of $2 trillion over several decades is called for, and power plant cost reduction, nuclear waste management and a proliferation-resistant international fuel cycle regime must all be addressed aggressively over the next decade or so. A critical determinant will be the degree to which carbon dioxide emissions from fossil-fuel use are priced, both in the industrial world and in the large emerging economies such as China, India and Brazil.

The economics of nuclear power are not the only factor governing its future use. Public acceptance also turns on issues of safety and nuclear waste, and the future of nuclear power in the U.S. and much of Europe remains in question. Regarding safety, it is essential that NRC regulations are enforced diligently, which has not always been the case.

In the scenario developed as part of the M.I.T. study, it emerged that the U.S. would approximately triple its nuclear deployment—to about 300,000 megawatts—if a terawatt were to be realized globally. The credibility of such a scenario will be largely determined in the forthcoming decade by the degree to which the first-mover incentives in the 2005 Energy Policy Act are exercised, by the capability of the government to start moving spent fuel from reactor sites and by whether the American political process results in a climate change policy that will significantly limit carbon dioxide emissions. SA

Extended temporary storage of waste should be an integral part of the disposal strategy.

MORE TO EXPLORE

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U.S. Nuclear Regulatory Commission: www.nrc.gov

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The Rise of *Renewable* Energy

Solar cells, wind turbines and biofuels are poised to become major energy sources. New policies could dramatically accelerate that evolution **BY DANIEL M. KAMMEN**

OVERVIEW

- Thanks to advances in technology, renewable sources could soon become large contributors to global energy.
- To hasten the transition, the U.S. must significantly boost its R&D spending on energy.
- The U.S. should also levy a fee on carbon to reward clean energy sources over those that harm the environment.

KENN BROWN

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No plan to substantially reduce greenhouse gas emissions can succeed through increases in energy efficiency alone. Because economic growth continues to boost the demand for energy—more coal for powering new factories, more oil for fueling new cars, more natural gas for heating new homes—carbon emissions will keep climbing despite the introduction of more energy-efficient vehicles, buildings and appliances. To counter the alarming trend of global warming, the U.S. and other countries must make a major commitment to developing renewable energy sources that generate little or no carbon.

Renewable energy technologies were suddenly and briefly fashionable three decades ago in response to the oil embargoes of the 1970s, but the interest and support were not sustained. In recent years, however, dramatic improvements in the performance and affordability of solar cells, wind turbines and biofuels—ethanol and other fuels derived from plants—have paved the way for mass commercialization. In addition to their environmental benefits, renewable sources promise to enhance America's energy security by reducing the country's reliance on fossil fuels from other nations. What is more, high and wildly fluctuating prices for oil and natural gas have made renewable alternatives more appealing.

We are now in an era where the op-

▼ A world of clean energy could rely on wind turbines and solar cells to generate its electricity and biofuels derived from switchgrass and other plants to power its vehicles.

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portunities for renewable energy are unprecedented, making this the ideal time to advance clean power for decades to come. But the endeavor will require a long-term investment of scientific, economic and political resources. Policymakers and ordinary citizens must demand action and challenge one another to hasten the transition.

Let the Sun Shine

SOLAR CELLS, also known as photovoltaics, use semiconductor materials to convert sunlight into electric current. They now provide just a tiny slice of the world's electricity: their global generating capacity of 5,000 megawatts (MW) is only 0.15 percent of the total generating capacity from all sources. Yet sunlight could potentially supply 5,000 times as much energy as the world currently consumes. And thanks to technology improvements, cost declines and favorable policies in many states and nations, the annual production of photovoltaics has increased by more than 25 percent a year for the past decade and by a remarkable 45 percent in 2005. The cells manufactured last year added 1,727 MW to worldwide generating capacity, with 833 MW made in Japan, 353 MW in Germany and 153 MW in the U.S.

Solar cells can now be made from a range of materials, from the traditional multicrystalline silicon wafers that still dominate the market to thin-film silicon cells and devices composed of plastic or organic semiconductors. Thin-film photovoltaics are cheaper to produce than crystalline silicon cells but are also less efficient at turning light into power. In laboratory tests, crystalline cells have achieved efficiencies of 30 percent or more; current commercial cells of this type range from 15 to 20 percent. Both laboratory and commercial efficiencies for all kinds of solar cells have risen steadily in recent years, indicating that an expansion of research efforts would further enhance the performance of solar cells on the market.

Solar photovoltaics are particularly easy to use because they can be installed in so many places—on the roofs or walls of homes and office buildings, in vast arrays in the desert, even sewn into clothing to power portable electronic devices. The state of California has joined Japan and Germany in leading a global push for solar installations; the "Million Solar Roof" commitment is intended to create 3,000 MW of new generating capacity in the state by 2018. Studies done by my research group, the Renewable and Appropriate Energy Laboratory at the University of California, Berkeley, show that annual production of solar photovoltaics in the U.S. alone could grow to 10,000 MW in just 20 years if current trends continue.

5,000 megawatts
Global generating capacity of solar power

37 percent
Top efficiency of experimental solar cells

20 to 25 cents
Cost per kilowatt-hour of solar power

The biggest challenge will be lowering the price of the photovoltaics, which are now relatively expensive to manufacture. Electricity produced by crystalline cells has a total cost of 20 to 25 cents per kilowatt-hour, compared with four to six cents for coal-fired electricity, five to seven cents for power produced by burning natural gas, and six to nine cents for biomass power plants. (The cost of nuclear power is harder to pin down because experts disagree on which expenses to include in the analysis; the estimated range is two to 12 cents per kilowatt-hour.) Fortunately, the prices of solar cells have fallen consistently over the past decade, largely because of improvements in manufacturing processes. In Japan, where 290 MW of solar generating capacity were added in 2005 and an even larger amount was exported, the cost of photovoltaics has declined 8 percent a year; in California, where 50 MW of solar power were installed in 2005, costs have dropped 5 percent annually.

Surprisingly, Kenya is the global leader in the number of solar power systems installed per capita (but not the number of watts added). More than 30,000 very small solar panels, each producing only 12 to 30 watts, are sold in that country annually. For an investment of as little as $100 for the panel and wiring, the system can be used to charge a car battery, which can then provide enough power to run a fluorescent lamp or a small black-and-white television for a few hours a day. More Kenyans adopt solar power every year than make connections to the country's electric grid. The panels typically use solar cells made of amorphous silicon; although these photovoltaics are only half as efficient as crystalline cells, their cost is so much lower (by a factor of at least four) that they are more affordable and useful for the two billion people worldwide who currently have no access to electricity. Sales of small solar power systems are booming in other African nations as well, and advances in low-cost photovoltaic manufacturing could accelerate this trend.

Furthermore, photovoltaics are not the only fast-growing form of solar power. Solar-thermal systems, which collect sunlight to generate heat, are also undergoing a resurgence. These systems have long been used to provide hot water for homes or factories, but they can also produce electricity without the need for expensive solar cells. In one design, for example, mirrors focus light on a Stirling engine, a high-efficiency device containing a working fluid that circulates between hot and cold chambers. The fluid expands as the sunlight heats it, pushing a piston that, in turn, drives a turbine.

In the fall of 2005 a Phoenix company called Stirling Energy Systems

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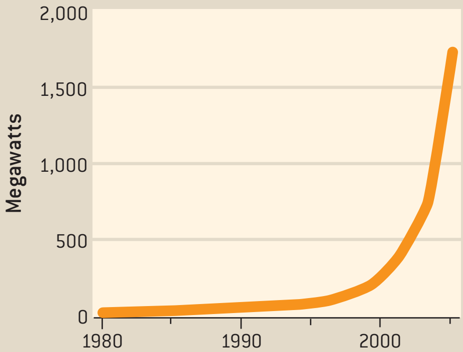
GROWING FAST, BUT STILL A SLIVER

Solar cells, wind power and biofuels are rapidly gaining traction in the energy markets, but they remain marginal providers compared with fossil-fuel sources such as coal, natural gas and oil.

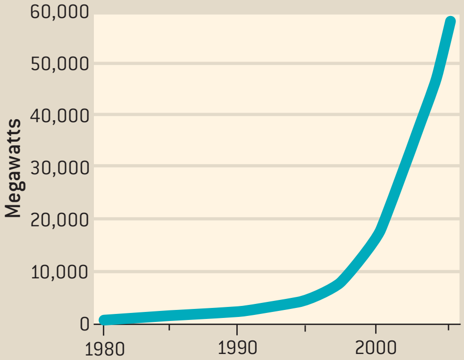
THE RENEWABLE BOOM

Since 2000 the commercialization of renewable energy sources has accelerated dramatically. The annual global production of solar cells, also known as photovoltaics, jumped 45 percent in 2005. The construction of new wind farms, particularly in Europe, has boosted the worldwide generating capacity of wind power 10-fold over the past decade. And the production of ethanol, the most common biofuel, soared to 36.5 billion liters last year, with the lion's share distilled from American-grown corn.

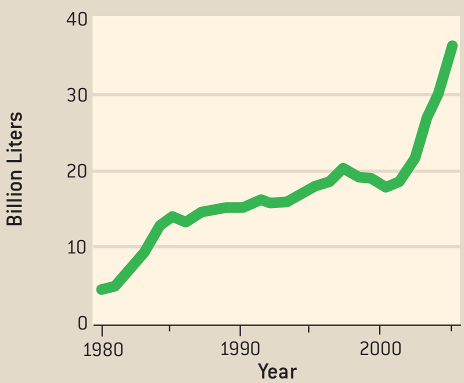
Photovoltaic Production



Wind Energy Generating Capacity



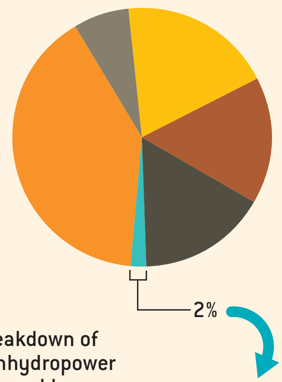
Ethanol Production



COMPETING ENERGY SOURCES

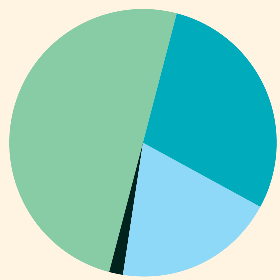
Fraction of global electricity generation

Coal · Nuclear · Oil · Hydropower · Natural gas · Nonhydropower renewables



Breakdown of nonhydropower renewables

Biomass · Geothermal · Wind · Solar



THE CHALLENGE AHEAD

Suppliers of renewable energy must overcome several technological, economic and political hurdles to rival the market share of the fossil-fuel providers. To compete with coal-fired power plants, for example, the prices of solar cells must continue to fall. The developers of wind farms must tackle environmental concerns and local opposition. Other promising renewable sources include generators driven by steam from geothermal vents and biomass power plants fueled by wood and agricultural wastes.

JEN CHRISTIANSEN; SOURCES: PV NEWS, BTM CONSULT, AWEA, EWEA, F. O. LICHT AND *BP STATISTICAL REVIEW OF WORLD ENERGY 2006*; SHARP ELECTRONICS CORPORATION (*solar arrays*); DON RYAN *AP Photo* (*wind turbines*); DOUG WILSON *Corbis* (*corn*)

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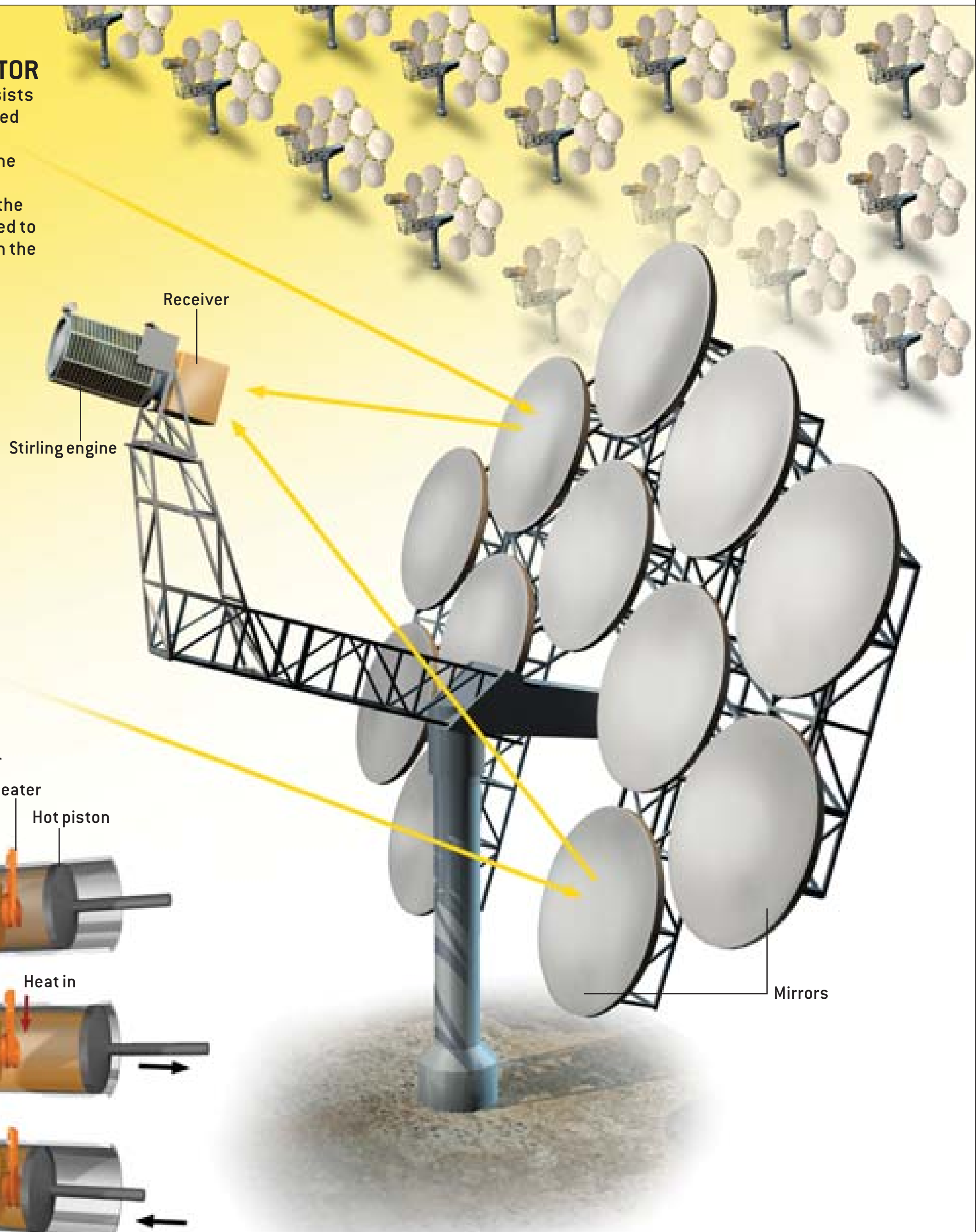
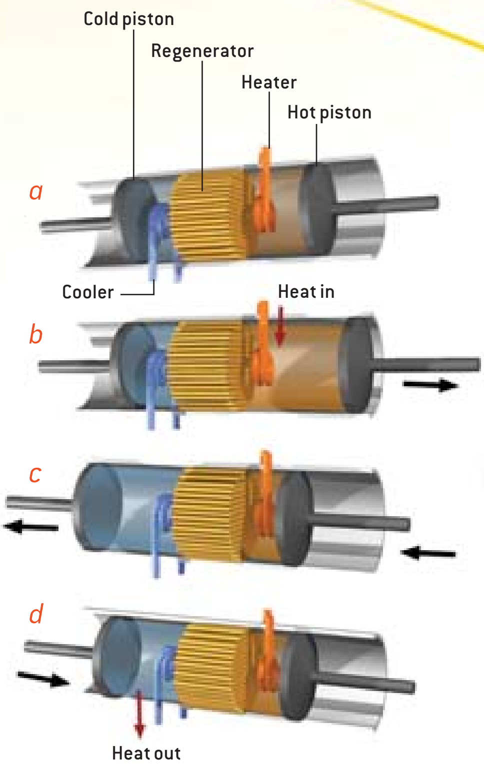
HOT POWER FROM MIRRORS

Solar-thermal systems, long used to provide hot water for homes or factories, can also generate electricity. Because these systems produce power from solar heat rather than light, they avoid the need for expensive photovoltaics.

SOLAR CONCENTRATOR

A solar-thermal array consists of thousands of dish-shaped solar concentrators, each attached to a Stirling engine that converts heat to electricity. The mirrors in the concentrator are positioned to focus reflected sunlight on the Stirling engine's receiver.





STIRLING ENGINE

A high-performance Stirling engine shuttles a working fluid, such as hydrogen gas, between two chambers (*a*). The cold chamber (*blue*) is separated from the hot chamber (*orange*) by a regenerator that maintains the temperature difference between them. Solar energy from the receiver heats the gas in the hot chamber, causing it to expand and move the hot piston (*b*). This piston then reverses direction, pushing the heated gas into the cold chamber (*c*). As the gas cools, the cold piston can easily compress it, allowing the cycle to start anew (*d*). The movement of the pistons drives a turbine that generates electricity in an alternator.

DON FOLEY; SOURCE: U.S. DEPARTMENT OF ENERGY

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announced that it was planning to build two large solar-thermal power plants in southern California. The company signed a 20-year power purchase agreement with Southern California Edison, which will buy the electricity from a 500-MW solar plant to be constructed in the Mojave Desert. Stretching across 4,500 acres, the facility will include 20,000 curved dish mirrors, each concentrating light on a Stirling engine about the size of an oil barrel. The plant is expected to begin operating in 2009 and could later be expanded to 850 MW. Stirling Energy Systems also signed a 20-year contract with San Diego Gas & Electric to build a 300-MW, 12,000-dish plant in the Imperial Valley. This facility could eventually be upgraded to 900 MW.

The financial details of the two California projects have not been made public, but electricity produced by present solar-thermal technologies costs between five and 13 cents per kilowatt-hour, with dish-mirror systems at the upper end of that range. Because the projects involve highly reliable technologies and mass production, however, the generation expenses are expected to ultimately drop closer to four to six cents per kilowatt-hour—that is, competitive with the current price of coal-fired power.

60,000 megawatts
Global generating capacity of wind power

0.5 percent
Fraction of U.S. electricity produced by wind turbines

1.9 cents
Tax credit for wind power, per kilowatt-hour of electricity

Blowing in the Wind

WIND POWER has been growing at a pace rivaling that of the solar industry. The worldwide generating capacity of wind turbines has increased more than 25 percent a year, on average, for the past decade, reaching nearly 60,000 MW in 2005. The growth has been nothing short of explosive in Europe—between 1994 and 2005, the installed wind power capacity in European Union nations jumped from 1,700 to 40,000 MW. Germany alone has more than 18,000 MW of capacity thanks to an aggressive construction program. The northern German state of Schleswig-Holstein currently meets one quarter of its annual electricity demand with more than 2,400 wind turbines, and in certain months wind power provides more than half the state's electricity. In addition, Spain has 10,000 MW of wind capacity, Denmark has 3,000 MW, and Great Britain, the Netherlands, Italy and Portugal each have more than 1,000 MW.

In the U.S. the wind power industry has accelerated dramatically in the past five years, with total generating capacity leaping 36 percent to 9,100 MW in 2005. Although wind turbines now produce only 0.5 percent of the nation's electricity, the potential for expansion is enormous, especially in the windy Great Plains states. (North Dakota, for example, has greater wind energy resources than Germany, but only 98 MW of generating capacity is installed there.) If the U.S. constructed enough wind farms to fully tap these resources, the turbines could generate as much as 11 trillion kilowatt-hours of electricity, or nearly three times the total amount produced from all energy sources in the nation last year. The wind industry has developed increasingly large and efficient turbines, each capable of yielding 4 to 6 MW. And in many locations, wind power is the cheapest form of new electricity, with costs ranging from four to seven cents per kilowatt-hour.

The growth of new wind farms in the U.S. has been spurred by a production tax credit that provides a modest subsidy equivalent to 1.9 cents per kilowatt-hour, enabling wind turbines to compete with coal-fired plants. Unfortunately, Congress has repeatedly threatened to eliminate the tax credit. Instead of instituting a long-term subsidy for wind power, the lawmakers have extended the tax credit on a year-to-year basis, and the continual uncertainty has slowed investment in wind farms. Congress is also threatening to derail a proposed 130-turbine farm off the coast of Massachusetts that would provide 468 MW of generating capacity, enough to power most of Cape Cod, Martha's Vineyard and Nantucket.

The reservations about wind power come partly from utility companies that are reluctant to embrace the new technology and partly from so-called NIMBY-ism. ("NIMBY" is an acronym for Not in My Backyard.) Although local concerns over how wind turbines will affect landscape views may have some merit, they must be balanced against the social costs of the alternatives. Because society's energy needs are growing relentlessly, rejecting wind farms often means requiring the construction or expansion of fossil fuel–burning power plants that will have far more devastating environmental effects.

Green Fuels

RESEARCHERS ARE ALSO pressing ahead with the development of biofuels that could replace at least a portion of the oil currently consumed by motor vehicles. The most common biofuel by far in the U.S. is ethanol, which is typically made from corn and blended with gasoline. The manufacturers of

THE AUTHOR

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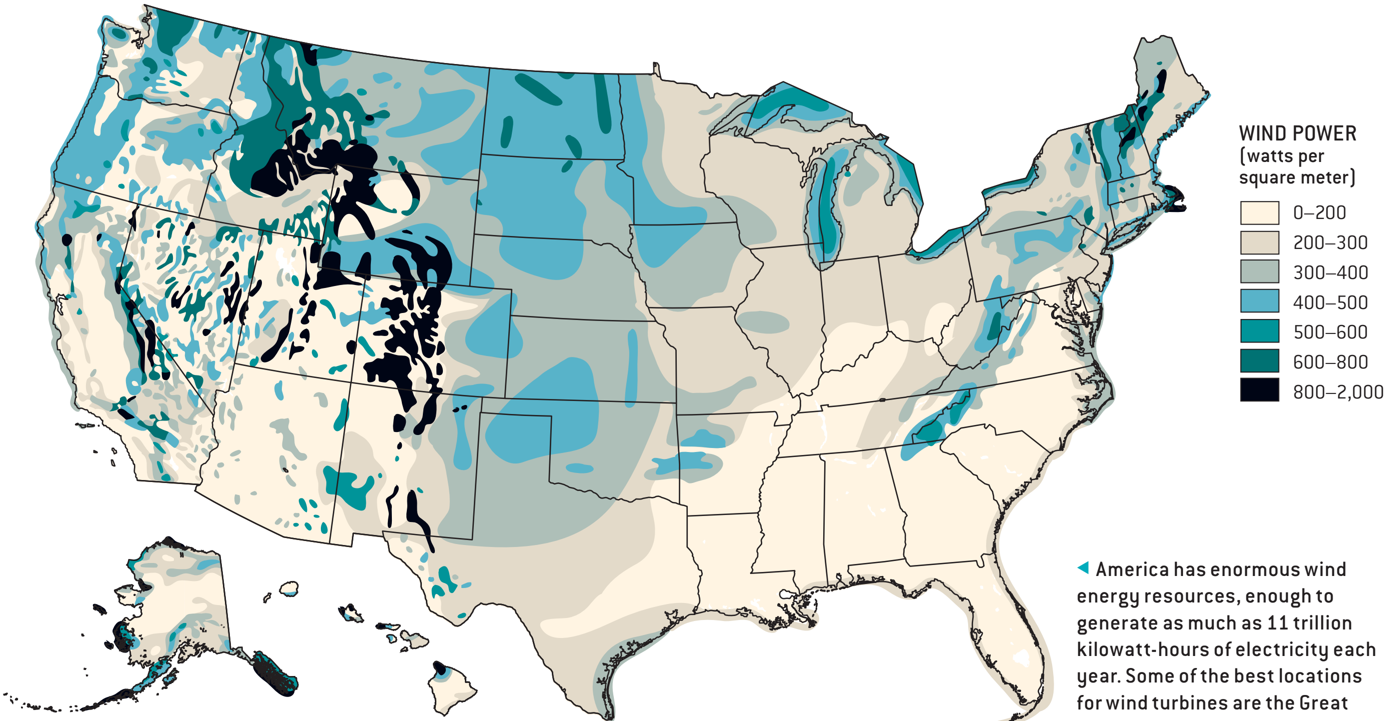

◀ America has enormous wind energy resources, enough to generate as much as 11 trillion kilowatt-hours of electricity each year. Some of the best locations for wind turbines are the Great Plains states, the Great Lakes and the mountain ridges of the Rockies and the Appalachians.

ethanol benefit from a substantial tax credit: with the help of the $2-billion annual subsidy, they sold more than 16 billion liters of ethanol in 2005 (almost 3 percent of all automobile fuel by volume), and production is expected to rise 50 percent by 2007. Some policymakers have questioned the wisdom of the subsidy, pointing to studies showing that it takes more energy to harvest the corn and refine the ethanol than the fuel can deliver to combustion engines. In a recent analysis, though, my colleagues and I discovered that some of these studies did not properly account for the energy content of the by-products manufactured along with the ethanol. When all the inputs and outputs were correctly factored in, we found that ethanol has a positive net energy of almost five megajoules per liter.

We also found, however, that ethanol's impact on greenhouse gas emissions is more ambiguous. Our best estimates indicate that substituting corn-based ethanol for gasoline reduces greenhouse gas emissions by 18 percent, but the analysis is hampered by large uncertainties regarding certain agricultural practices, particularly the environmental costs of fertilizers. If we use different assumptions about these practices, the results of switching to ethanol range from a 36 percent drop in emissions to a 29 percent increase. Although corn-based ethanol may help the U.S. reduce its reliance on foreign oil, it will probably not do much to slow global warming unless the production of the biofuel becomes cleaner.

But the calculations change substantially when the ethanol is made from cellulosic sources: woody plants such as switchgrass or poplar. Whereas most makers of corn-based ethanol burn fossil fuels to provide the heat for fermentation, the producers of cellulosic ethanol burn lignin—an unfermentable part of the organic material—to heat the plant sugars. Burning lignin does not add any greenhouse gases to the atmosphere, because the emissions are offset by the carbon dioxide absorbed during the growth of the plants used to make the ethanol. As a result, substituting cellulosic ethanol for gasoline can slash greenhouse gas emissions by 90 percent or more.

Another promising biofuel is so-called green diesel. Researchers have produced this fuel by first gasifying biomass—heating organic materials enough that they release hydrogen and carbon monoxide—and then converting these compounds into long-chain hydrocarbons using the Fischer-Tropsch process. (During World War II, German engineers employed these chemical reactions to make synthetic motor fuels out of coal.) The result would be an economically competitive liquid fuel for motor vehicles that would add virtually

16.2 billion
Liters of ethanol produced in the U.S. in 2005

2.8 percent
Ethanol's share of all automobile fuel by volume

$2 billion
Annual subsidy for corn-based ethanol

JEN CHRISTIANSEN; SOURCE: NATIONAL RENEWABLE ENERGY LABORATORY

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PLUGGING HYBRIDS

The environmental benefits of renewable biofuels would be even greater if they were used to fuel plug-in hybrid electric vehicles (PHEVs). Like more conventional gasoline-electric hybrids, these cars and trucks combine internal-combustion engines with electric motors to maximize fuel efficiency, but PHEVs have larger batteries that can be recharged by plugging them into an electrical outlet. These vehicles can run on electricity alone for relatively short trips; on longer trips, the combustion engine kicks in when the batteries no longer have sufficient juice. The combination can drastically reduce gasoline consumption: whereas conventional sedans today have a fuel economy of about 30 miles per gallon (mpg) and nonplug-in hybrids such as the Toyota Prius average about 50 mpg, PHEVs could get an equivalent of 80 to 160 mpg. Oil use drops still further if the combustion engines in PHEVs run on biofuel blends such as E85, which is a mixture of 15 percent gasoline and 85 percent ethanol.

If the entire U.S. vehicle fleet were replaced overnight with PHEVs, the nation's oil consumption would decrease by 70 percent or more, completely eliminating the need for petroleum imports. The switch would have equally profound implications for protecting the earth's fragile climate, not to mention the elimination of smog. Because most of the energy for cars would come from the electric grid instead of from fuel tanks, the environmental impacts would be concentrated in a few thousand power plants instead of in hundreds of millions of vehicles. This shift would focus the challenge of climate protection squarely on the task of reducing the greenhouse gas emissions from electricity generation.

PHEVs could also be the salvation of the ailing American auto industry. Instead of continuing to lose market share to foreign companies, U.S. automakers could become competitive again by retooling their factories to produce PHEVs that are significantly more fuel-efficient than the nonplug-in hybrids now sold by Japanese companies. Utilities would also benefit from the transition because most owners of PHEVs would recharge their cars at night, when power is cheapest, thus helping to smooth the sharp peaks and valleys in demand for electricity. In California, for example, the replacement of 20 million conventional cars with PHEVs would increase nighttime electricity demand to nearly the same level as daytime demand, making far better use of the grid and the many power plants that remain idle at night. In addition, electric vehicles not in use during the day could supply electricity to local distribution networks at times when the grid was under strain. The potential benefits to the electricity industry are so compelling that utilities may wish to encourage PHEV sales by offering lower electricity rates for recharging vehicle batteries.

Most important, PHEVs are not exotic vehicles of the distant future. DaimlerChrysler has already introduced a PHEV prototype, a plug-in hybrid version of the Mercedes-Benz Sprinter Van that has 40 percent lower gasoline consumption than the conventionally powered model. And PHEVs promise to become even more efficient as new technologies improve the energy density of batteries, allowing the vehicles to travel farther on electricity alone.

—D.M.K.

HYMOTION

no greenhouse gases to the atmosphere. Oil giant Royal Dutch/Shell is currently investigating the technology.

The Need for R&D

EACH OF THESE renewable sources is now at or near a tipping point, the crucial stage when investment and innovation, as well as market access, could enable these attractive but generally marginal providers to become major contributors to regional and global energy supplies. At the same time, aggressive policies designed to open markets for renewables are taking hold at city, state and federal levels around the world. Governments have adopted these policies for a wide variety of reasons: to promote market diversity or energy security, to bolster industries and jobs, and to protect the environment on both the local and global scales. In the U.S. more than 20 states have adopted standards setting a minimum for the fraction of electricity that must be supplied with renewable sources. Germany plans to generate 20 percent of its electricity from renewables by 2020, and Sweden intends to give up fossil fuels entirely.

Even President George W. Bush said, in his now famous State of the Union address this past January, that the U.S. is "addicted to oil." And although Bush did not make the link to global warming, nearly all scientists agree that humanity's addiction to fossil fuels is disrupting the earth's climate. The time for action is now, and at last the tools exist to alter energy production and consumption in ways that simultaneously benefit the economy and the environment. Over the past 25 years, however, the public and private funding of research and development in the energy sector has withered. Between 1980 and 2005 the fraction of all U.S. R&D spending devoted to energy declined from 10 to 2 percent. Annual public R&D funding for energy sank from \$8 billion to \$3 billion (in 2002 dollars); private R&D plummeted from \$4 billion to \$1 billion [*see box on next page*].

To put these declines in perspective, consider that in the early 1980s energy companies were investing more in R&D than were drug companies, whereas today investment by energy firms is an order of magnitude lower. Total private R&D funding for the entire energy sector is less than that of a single

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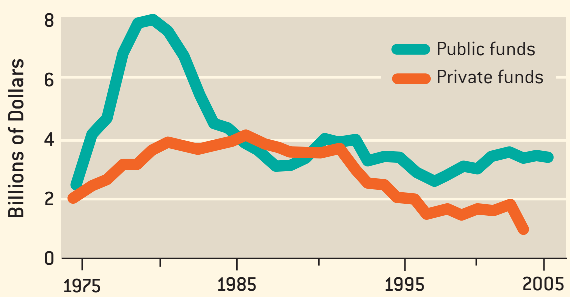
large biotech company. (Amgen, for example, had R&D expenses of $2.3 billion in 2005.) And as R&D spending dwindles, so does innovation. For instance, as R&D funding for photovoltaics and wind power has slipped over the past quarter of a century, the number of successful patent applications in these fields has fallen accordingly. The lack of attention to long-term research and planning has significantly weakened our nation's ability to respond to the challenges of climate change and disruptions in energy supplies.

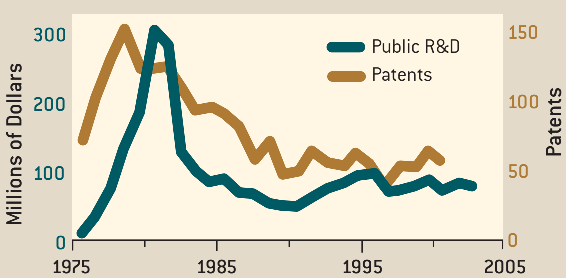
R&D IS KEY

Spending on research and development in the U.S. energy sector has fallen steadily since its peak in 1980. Studies of patent activity suggest that the drop in funding has slowed the development of renewable energy technologies. For example, the number of successful patent applications in photovoltaics and wind power has plummeted as R&D spending in these fields has declined.

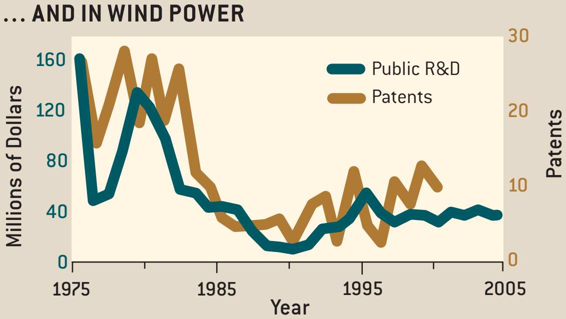
U.S. R&D SPENDING IN THE ENERGY SECTOR



LAGGING INNOVATION IN PHOTOVOLTAICS …



… AND IN WIND POWER



Spending amounts are expressed in 2002 dollars to adjust for inflation.

Calls for major new commitments to energy R&D have become common. A 1997 study by the President's Committee of Advisors on Science and Technology and a 2004 report by the bipartisan National Commission on Energy Policy both recommended that the federal government double its R&D spending on energy. But would such an expansion be enough? Probably not. Based on assessments of the cost to stabilize the amount of carbon dioxide in the atmosphere and other studies that estimate the success of energy R&D programs and the resulting savings from the technologies that would emerge, my research group has calculated that public funding of $15 billion to $30 billion a year would be required—a fivefold to 10-fold increase over current levels.

Greg F. Nemet, a doctoral student in my laboratory, and I found that an increase of this magnitude would be roughly comparable to those that occurred during previous federal R&D initiatives such as the Manhattan Project and the Apollo program, each of which produced demonstrable economic benefits in addition to meeting its objectives. American energy companies could also boost their R&D spending by a factor of 10, and it would still be below the average for U.S. industry overall. Although government funding is essential to supporting early-stage technologies, private-sector R&D is the key to winnowing the best ideas and reducing the barriers to commercialization.

Raising R&D spending, though, is not the only way to make clean energy a national priority. Educators at all grade levels, from kindergarten to college, can stimulate public interest and activism by teaching how energy use and production affect the social and natural environment. Nonprofit organizations can establish a series of contests that would reward the first company or private group to achieve a challenging and worthwhile energy goal, such as constructing a building or appliance that can generate its own power or developing a commercial vehicle that can go 200 miles on a single gallon of fuel. The contests could be modeled after the Ashoka awards for pioneers in public policy and the Ansari X Prize for the developers of space vehicles. Scientists and entrepreneurs should also focus on finding clean, affordable ways to meet the energy needs of people in the developing world. My colleagues and I, for instance, recently detailed the environmental benefits of improving cooking stoves in Africa.

But perhaps the most important step toward creating a sustainable energy economy is to institute market-based schemes to make the prices of carbon fuels reflect their social cost. The use of coal, oil and natural gas imposes a huge collective toll on society, in the form of health care expenditures for ailments caused by air pollution, military spending to secure oil supplies, environmental damage from mining operations, and the potentially devastating economic impacts of global warming. A fee on carbon emissions would provide a simple, logical and transparent method to reward renewable, clean energy sources over those that harm the economy and the environment. The tax revenues could pay for some of the social costs of carbon emissions, and a portion could be des-

JEN CHRISTIANSEN; SOURCE: *REVERSING THE INCREDIBLE SHRINKING ENERGY R&D BUDGET*, D. M. KAMMEN AND G. NEMET IN *ISSUES IN SCIENCE AND TECHNOLOGY*, FALL 2005

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THE LEAST BAD FOSSIL FUEL

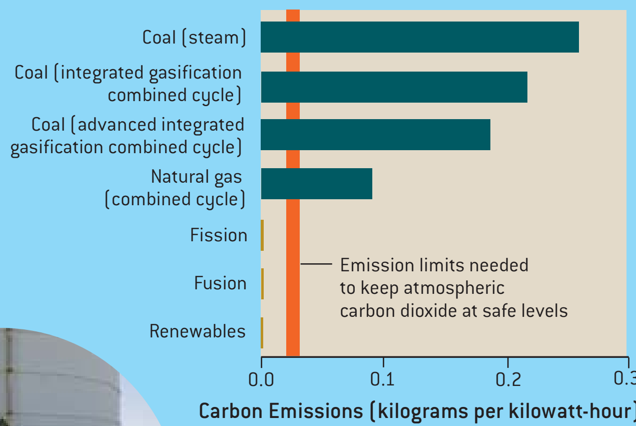
Although renewable energy sources offer the best way to radically cut greenhouse gas emissions, generating electricity from natural gas instead of coal can significantly reduce the amount of carbon added to the atmosphere. Conventional coal-fired power plants emit 0.25 kilogram of carbon for every kilowatt-hour generated. (More advanced coal-fired plants produce about 20 percent less carbon.) But natural gas (CH_4) has a higher proportion of hydrogen and a lower proportion of carbon than coal does. A combined-cycle power plant that burns natural gas emits only about 0.1 kilogram of carbon per kilowatt-hour (*graph at right*).

Unfortunately, dramatic increases in natural gas use in the U.S. and other countries have driven up the cost of the fuel. For the past decade, natural gas has been the fastest-growing source of fossil-fuel energy, and it now supplies almost 20 percent of America's electricity. At the same time, the price of natural gas has risen from an average of $2.50 to $3 per million Btu in 1997 to more than $7 per million Btu today.

The price increases have been so alarming that in 2003, then Federal Reserve Board Chair Alan Greenspan warned that the U.S. faced a natural gas crisis. The primary solution proposed by the White House and some in Congress was to increase gas production. The 2005 Energy Policy Act included large subsidies to support gas producers, increase exploration and expand imports of liquefied natural gas (LNG). These measures, however, may not enhance energy security, because most of the imported LNG would come from some of the same OPEC countries that supply petroleum to the U.S. Furthermore, generating electricity from even the cleanest natural gas power plants would still emit too much carbon to achieve the goal of keeping carbon dioxide in the atmosphere below 450 to 550 parts per million by volume. (Higher levels could have disastrous consequences for the global climate.)

Improving energy efficiency and developing renewable sources can be faster, cheaper and cleaner and provide more security than developing new gas supplies. Electricity from a wind farm costs less than that produced by a natural gas power plant if the comparison factors in the full cost of plant construction and forecasted gas prices. Also, wind farms and solar arrays can be built more rapidly than large-scale natural gas plants. Most critically, diversity of supply is America's greatest ally in maintaining a competitive and innovative energy sector. Promoting renewable sources makes sense strictly on economic grounds, even before the environmental benefits are considered. *—D.M.K.*

HOW POWER PLANT EMISSIONS STACK UP



ignated to compensate low-income families who spend a larger share of their income on energy. Furthermore, the carbon fee could be combined with a cap-and-trade program that would set limits on carbon emissions but also allow the cleanest energy suppliers to sell permits to their dirtier competitors. The federal government has used such programs with great success to curb other pollutants, and several northeastern states are already experimenting with greenhouse gas emissions trading.

Best of all, these steps would give energy companies an enormous financial incentive to advance the development and commercialization of renewable energy sources. In essence, the U.S. has the opportunity to foster an entirely new industry. The threat of climate change can be a rallying cry for a clean-technology revolution that would strengthen the country's manufacturing base, create thousands of jobs and alleviate our international trade deficits—instead of importing foreign oil, we can export high-efficiency vehicles, appliances, wind turbines and photovoltaics. This transformation can turn the nation's energy sector into something that was once deemed impossible: a vibrant, environmentally sustainable engine of growth. SA

MORE TO EXPLORE

Reversing the Incredible Shrinking Energy R&D Budget. D. M. Kammen and G. F. Nemet in *Issues in Science and Technology,* pages 84–88; Fall 2005.

Science and Engineering Research That Values the Planet. A. Jacobson and D. M. Kammen in *The Bridge,* Vol. 35, No. 4, pages 11–17; Winter 2005.

Renewables 2005: Global Status Report. Renewable Energy Policy Network for the 21st Century. Worldwatch Institute, 2005.

Ethanol Can Contribute to Energy and Environmental Goals. A. E. Farrell, R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare and D. M. Kammen in *Science,* Vol. 311, pages 506–508; January 27, 2006.

All these papers are available online at **http://rael.berkeley.edu/papers.html**

JEN CHRISTIANSEN; SOURCE: PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY; STEVEN SENNE *AP Photo (natural gas plant)*

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▶ Will motorists someday fill up their tanks with hydrogen? Many complex challenges must be overcome before a hydrogen-fueled future can become a reality.

High Hopes for

MATT VINCENT ILLUSTRATION; JOE RAEDLE *Getty Images* (*photograph*)

Using hydrogen to fuel cars may eventually slash oil consumption and carbon emissions, but it will take some time **BY JOAN OGDEN**

OVERVIEW

- Hydrogen fuel-cell cars could become commercially feasible if automakers succeed in developing safe, inexpensive, durable models that can travel long distances before refueling.
- Energy companies could produce large amounts of hydrogen at prices competitive with gasoline, but building the infrastructure of distribution will be costly.

Developing cleaner power sources for transportation is perhaps the trickiest piece of the energy puzzle. The difficulty stems from two discouraging facts. First, the number of vehicles worldwide, now 750 million, is expected to triple by 2050, thanks largely to the expanding buying power of customers in China, India and other rapidly developing countries. And second, 97 percent of transportation fuel currently comes from crude oil.

In the near term, improving fuel economy is the best way to slow the rise in oil use and greenhouse gas emissions from cars and trucks. But even if automakers triple the efficiency of their fleets and governments support mass transit and smart-growth strategies that lessen the public's reliance on cars, the explosive growth in the number of vehicles around the world will severely limit any reductions in oil consumption and carbon dioxide emissions. To make deeper cuts, the transportation sector needs to switch to low-carbon, nonpetroleum fuels. Liquid fuels derived from woody plants or synthesized from tar sands or coal may play important roles. Over the long term, however, the most feasible ways to power vehicles with high efficiency and zero emissions are through connections to the electric grid or the use of hydrogen as a transportation fuel.

Unfortunately, the commercialization of electric vehicles has been stymied by a daunting obstacle: even large arrays of batteries cannot store enough charge to keep cars running for distances comparable to gasoline engines. For this reason, most auto companies have abandoned the technology. In contrast, fuel-cell vehicles—which combine hydrogen fuel and oxygen from the air to generate the power to run electric motors—face fewer technical hurdles and have the enthusiastic support of auto manufacturers, energy companies and policymakers. Fuel-cell vehicles are several times as efficient as today's conventional gasoline cars, and their only tailpipe emission is water vapor.

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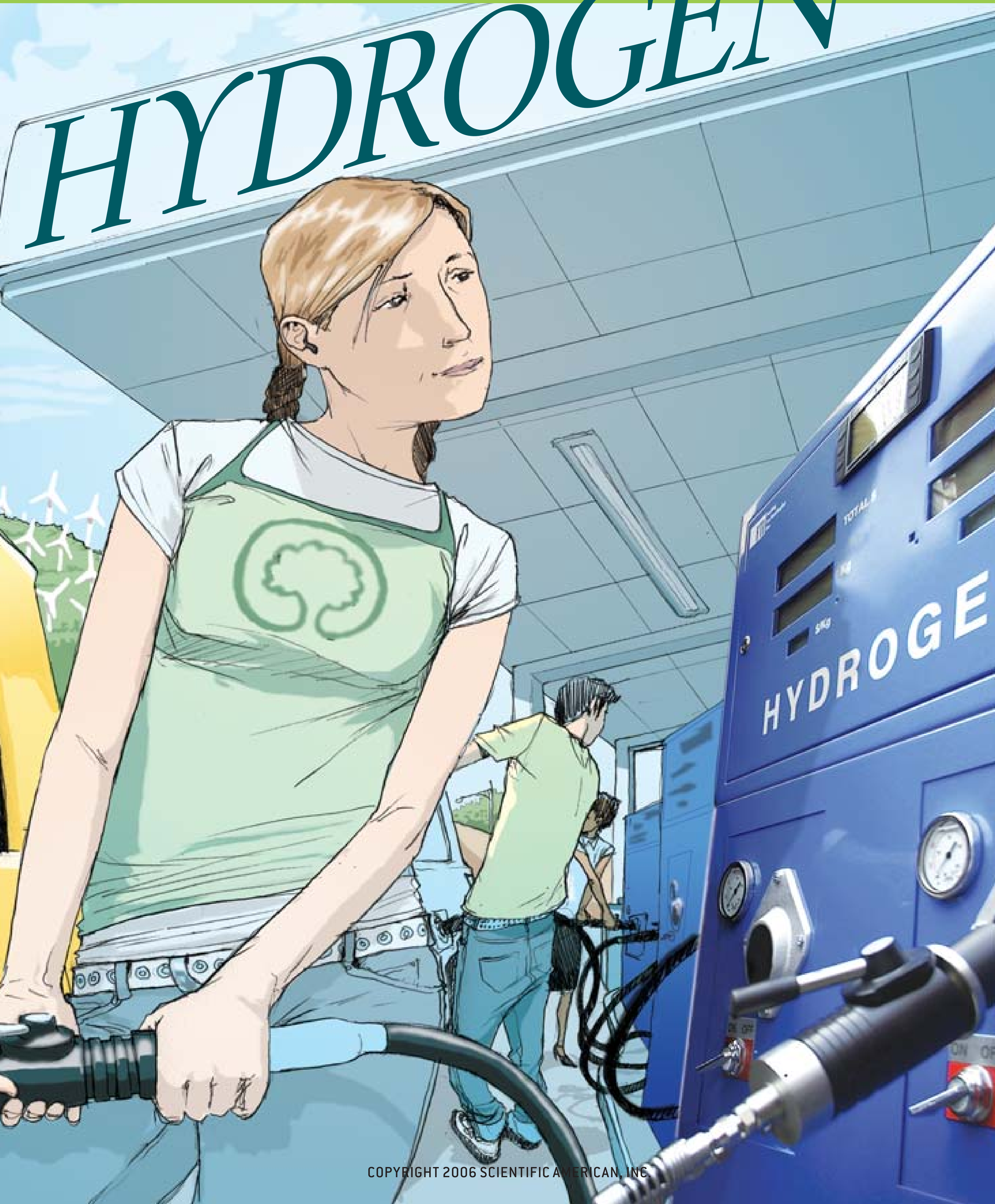
HYDROGEN



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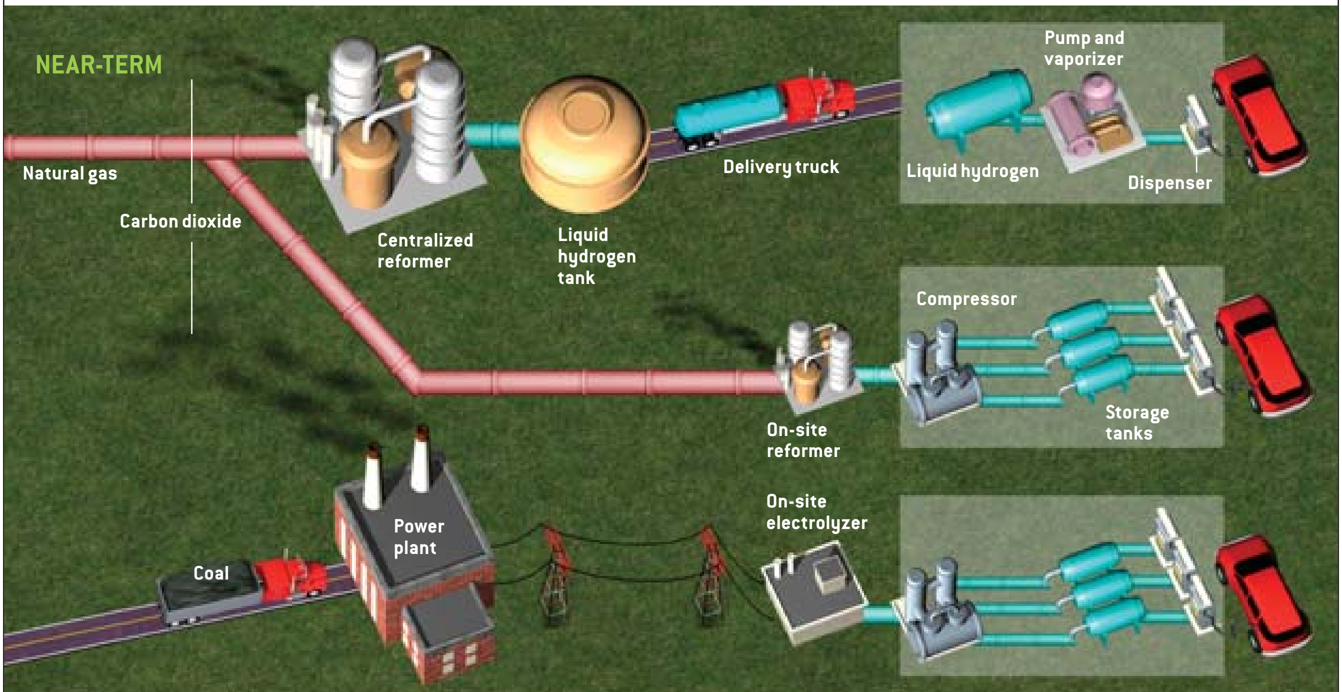
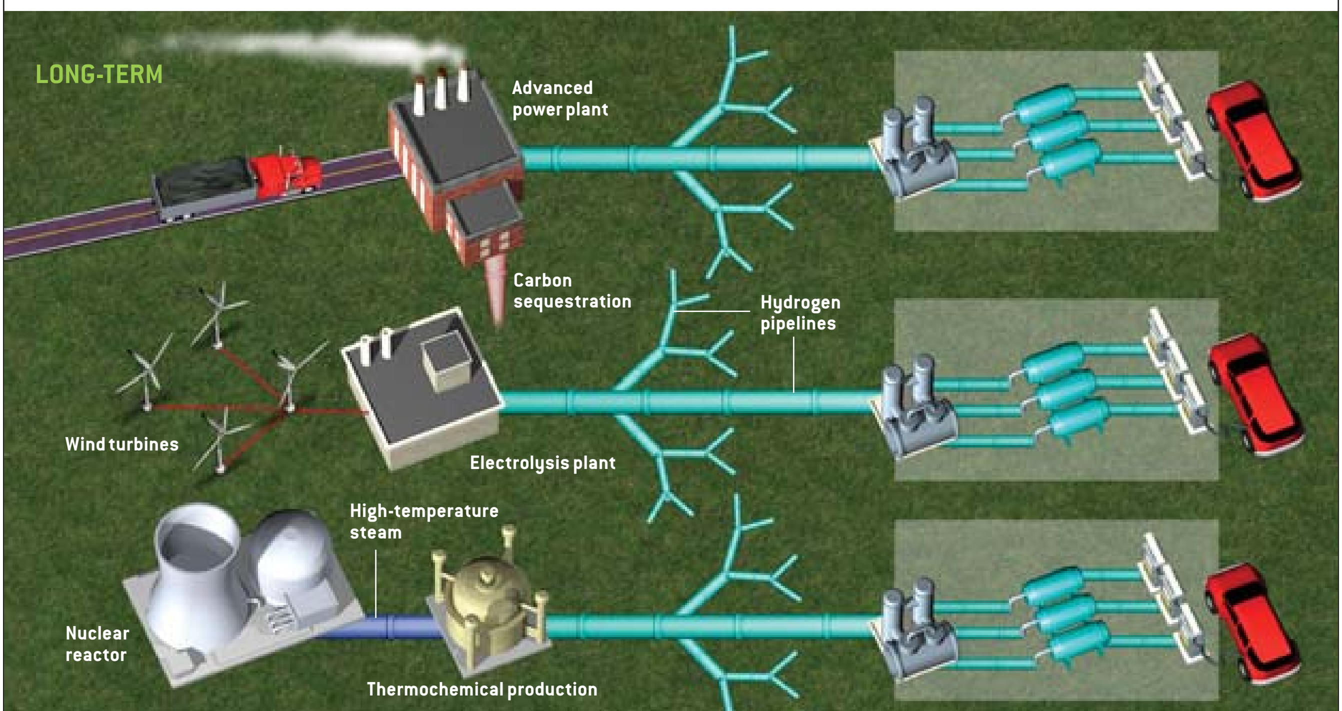
OPTIONS FOR A HYDROGEN INFRASTRUCTURE

Energy companies could manufacture and distribute hydrogen fuel in many ways. In the near term, the most likely option is extracting hydrogen from natural gas, either in centralized reformers that supply fueling stations by delivery truck or in smaller on-site reformers located at the stations. The fueling stations could also use electricity from the power grid to make hydrogen by electrolyzing water. All these options, however, would produce greenhouse gas emissions (assuming that fossil fuels are used to make the electricity).



In the long term, policymakers should encourage cleaner methods. Advanced power plants could extract hydrogen from coal and bury the carbon dioxide deep underground. Wind turbines and other renewable energy sources could provide the power for electrolysis. And high-temperature steam from nuclear reactors could generate hydrogen through the thermochemical splitting of water.



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What is more, hydrogen fuel can be made without adding any greenhouse gases to the atmosphere. For example, the power needed to produce hydrogen from electrolysis—using electricity to split water into hydrogen and oxygen—can come from renewable energy sources such as solar cells, wind turbines, hydroelectric plants and geothermal facilities. Alternatively, hydrogen can be extracted from fossil fuels such as natural gas and coal, and the carbon by-products can be captured and sequestered underground.

Before a hydrogen-fueled future can become a reality, however, many complex challenges must be overcome. Carmakers must learn to manufacture new types of vehicles, and consumers must find them attractive enough to buy. Energy companies must adopt cleaner techniques for producing hydrogen and build a new fuel infrastructure that will eventually replace the existing systems for refining and distributing gasoline. Hydrogen will not fix all our problems tomorrow; in fact, it could be decades before it starts to reduce greenhouse gas emissions and oil use on a global scale. It is important to recognize that a hydrogen transition will be a marathon, not a sprint.

The Fuel-Cell Future

OVER THE PAST DECADE, 17 countries have announced national programs to develop hydrogen energy, committing billions of dollars in public funds. In North America more than 30 U.S. states and several Canadian provinces are developing similar plans. Most major car companies are demonstrating prototype hydrogen vehicles and investing hundreds of millions of dollars into R&D efforts. Honda, Toyota and General Motors have announced plans to commercialize fuel-cell vehicles sometime between 2010 and 2020. Automakers and energy companies such as Shell, Chevron and BP are working with governments to introduce the first fleets of hydrogen vehicles, along with small refueling networks in California, the northeastern U.S., Europe and China.

The surge of interest in hydrogen stems not only from its long-term environmental benefits but also from its potential to stimulate innovation. Auto manufacturers have embraced fuel-cell cars because they promise to become a superior consumer product. The technology offers quiet operation, rapid acceleration and low maintenance costs. Replacing internal-combustion engines with fuel cells and electric motors eliminates the need for many mechanical and hydraulic subsystems; this change gives automakers more flexibility in designing these cars and the ability to manufacture them more efficiently. What is more, fuel-cell vehicles could provide their owners with a mobile source of electricity that might be used for recreational or business purposes. During periods of peak power usage, when electricity is most expensive, fuel-cell cars could also act as distributed generators, providing relatively cheap supplemental power for offices or homes while parked nearby.

Automakers, however, must address several technical and cost issues to make fuel-cell cars more appealing to consumers. A key component of the automotive fuel cell is the proton-exchange membrane (PEM), which separates the hydrogen fuel from the oxygen. On one side of the membrane, a catalyst splits the hydrogen atoms into protons and electrons; then the protons cross the membrane and combine with oxygen atoms on the other side. Manufacturers have reduced the weight and volume of PEM fuel cells so that they easily fit inside a compact car. But the membranes degrade with use—current automotive PEM fuel cells last only about 2,000 hours, less than half the 5,000-hour lifetime needed for commercial vehicles. Companies are developing more durable membranes, however, and in late 2005 researchers at 3M, the corporation best known for Scotch tape and Post-it notes, reported new designs that might take fuel cells to 4,000 hours and beyond within the next five years.

Another big challenge is reducing the expense of the fuel cells. Today's fuel-cell cars are handmade specialty items that cost about $1 million apiece. Part of the reason for the expense is the small scale of the test fleets; if fuel-cell cars were mass-produced, the cost of their propulsion systems would most likely drop to a more manageable $6,000 to $10,000. That price is equivalent to $125 per kilowatt of engine power, which is about four times as high as the $30-per-kilowatt cost of a comparable internal-combustion engine. Fuel cells may require new materials and manufacturing methods to reach parity with gasoline engines. Car companies may also be able to lower costs by creatively redesigning the vehicles to fit the unique characteristics of the fuel cell. GM officials have stated that fuel-cell cars might ultimately become less expensive than gasoline vehicles because they would have fewer moving parts and a more flexible architecture.

Automobile engineers must also figure out how to store enough hydrogen in a fuel-cell car to ensure a reasonable driving range—say, 300 miles. Storing hydrogen in its gaseous state requires large, high-pressure cylinders. Although liquid hydrogen takes up less space, it must be supercooled to temperatures below –253 degrees Celsius (–423 degrees Fahrenheit). Automakers are exploring the use of metal hydride systems that adsorb hydrogen under pressure, but these devices tend to be heavy (about 300 kilograms). Finding a better storage method is a major thrust of hydrogen R&D worldwide. In the absence of a breakthrough technology, most fuel-cell ve-

It is important to recognize that a hydrogen transition will be a marathon, not a sprint.

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hicles today opt for the simplicity of storing the hydrogen as a compressed gas. With clever packaging and increased pressure, these cars are approaching viable travel ranges without compromising trunk space or vehicle weight. In 2005 GM, Honda and Toyota demonstrated compact fuel-cell cars with a 300-mile range using hydrogen gas compressed at 70 megapascals. (Atmospheric pressure at sea level is about 0.1 megapascal.)

Finally, safety is a necessary precondition for introducing any new fuel. Although hydrogen is flammable, it has a higher ignition temperature than gasoline and disperses in the air much more quickly, reducing the risk of fire. On the downside, a much wider range of concentrations of hydrogen is flammable, and a hydrogen flame is barely visible. Oil refineries, chemical plants and other industrial facilities already handle vast quantities of hydrogen without incident, and with proper engineering it can be made safe for consumer applications as well. The U.S. Department of Energy and other groups are currently developing safety codes and standards for hydrogen fuel.

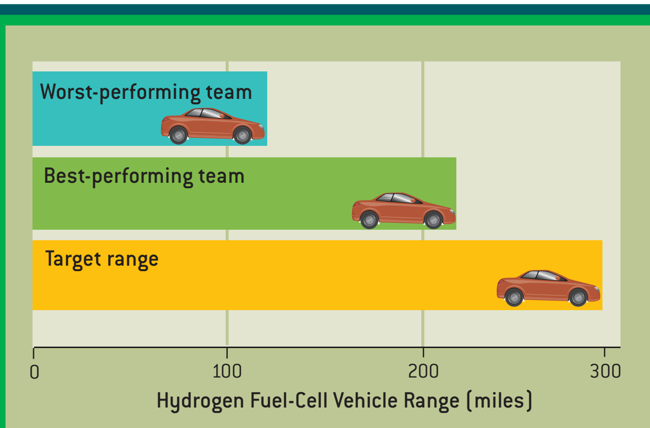
Once hydrogen cars are introduced, how soon could they capture a large share of the market and start to significantly reduce carbon emissions and oil use? Because cars last about 15 years, it would take at least that long to switch over the entire fleet. Typically after a new automotive technology undergoes precommercial research, development and demonstration, it is introduced to the market in a single car model and only later appears in a variety of vehicles. (For example, hybrid gas-electric engines were first developed for compact sedans and later incorporated into SUVs.) Costs generally fall as production volumes increase, making the innovation more attractive. It can take 25 to 60 years for a new technology to penetrate a sizable fraction of the fleet. Although fundamental research on hybrid vehicles began in the 1970s, it was not until 1993 that Toyota began development of the Prius hybrid. Initial sales began in late 1997, but eight years later hybrid models from several manufacturers still accounted for only 1.2 percent of new vehicle sales in the U.S.

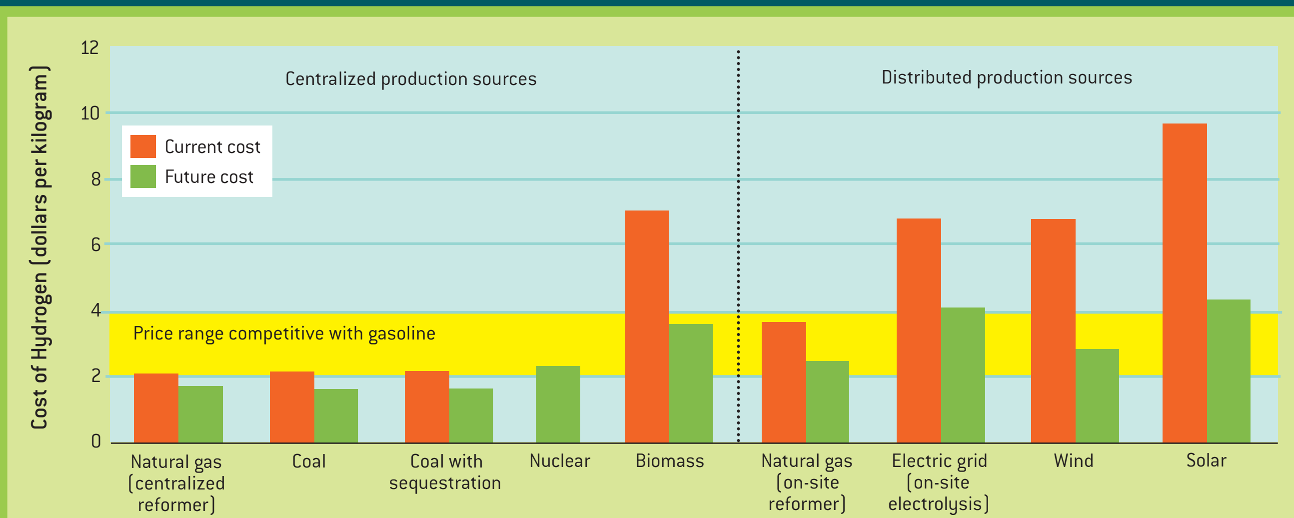
Harvesting Hydrogen

LIKE ELECTRICITY, hydrogen must be produced from some energy source. Currently the vast majority of hydrogen is obtained from the high-temperature processing of natural gas and petroleum. Oil refineries use hydrogen to purify petroleum-derived fuels, and chemical manufacturers employ the gas to make ammonia and other compounds. Hydrogen production now consumes 2 percent of global energy, and its share is growing rapidly. If all this hydrogen were devoted to

HURDLES FOR HYDROGEN

One of the challenges facing fuel-cell cars is extending their range. The U.S. Department of Energy's National Renewable Energy Laboratory recently measured the ranges of 59 fuel-cell cars made by four industry teams (*right*). Even the best-performing team fell short of the 300-mile range needed for a commercial vehicle. Another challenge is lowering the price of hydrogen fuel. Making hydrogen from renewable energy sources such as wind, solar and biomass power is currently too expensive, but future technologies could make zero-emissions production more affordable (*below*).





JEN CHRISTIANSEN; SOURCES: NATIONAL RENEWABLE ENERGY LABORATORY (*vehicle ranges*); NATIONAL RESEARCH COUNCIL AND NATIONAL ACADEMY OF ENGINEERING (*hydrogen prices*); JANET CHAO (*cars*)

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fuel-cell cars, it would power about 150 million vehicles, or about 20 percent of the world's fleet. Although most hydrogen is produced and immediately used inside refineries or chemical plants, some 5 to 10 percent is delivered to distant locations by truck or pipeline. In the U.S. this delivery system carries enough energy to fuel several million cars, and it could serve as a springboard to a hydrogen economy.

Making hydrogen from fossil fuels, however, generates carbon dioxide as a by-product. If hydrogen were produced from natural gas, the most common method today, and used in an efficient fuel-cell car, the total greenhouse gas emissions would work out to be about 110 grams per kilometer driven. This amount is somewhat less than the total emissions from a gasoline hybrid vehicle (150 grams per kilometer) and significantly less than those from today's conventional gasoline cars (195 grams per kilometer).

The ultimate goal, though, is to produce hydrogen with little or no greenhouse gas emissions. One option is to capture the carbon dioxide emitted when extracting hydrogen from fossil fuels and inject it deep underground or into the ocean. This process could enable large-scale, clean production of hydrogen at relatively low cost, but establishing the technical feasibility and environmental safety of carbon sequestration will be crucial. Another idea is biomass gasification—heating organic materials such as wood and crop wastes so that they release hydrogen and carbon monoxide. (This technique does not add greenhouse gases to the atmosphere, because the carbon emissions are offset by the carbon dioxide absorbed by the plants when they were growing.) A third possibility is the electrolysis of water using power generated by renewable energy sources such as wind turbines or solar cells.

Although electrolysis and biomass gasification face no major technical hurdles, the current costs for producing hydrogen using these methods are high: $6 to $10 per kilogram. (A kilogram of hydrogen has about the same energy content as a gallon of gasoline, but it will propel a car several times as far because fuel cells are more efficient than conventional gasoline engines.) According to a recent assessment by the National Research Council and the National Academy of Engineering, however, future technologies and large-scale production and distribution could lower the price of hydrogen at the pump to $2 to $4 per kilogram [*see box on opposite page*]. In this scenario, hydrogen in a fuel-cell car would cost less per kilometer than gasoline in a conventional car today.

Nuclear energy could also provide the power for electrolysis, although producing hydrogen this way would not be significantly cheaper than using renewable sources. In addition, nuclear plants could generate hydrogen without electrolysis: the intense heat of the reactors can split water in a thermochemical reaction. This process might produce hydrogen more cheaply, but its feasibility has not yet been proved. Moreover, any option involving nuclear power has the same drawbacks that have dogged the nuclear electric power industry for decades: the problems of radioactive waste, proliferation and public acceptance.

GENERAL MOTORS

▲ A major advantage of the Hy-wire prototype fuel-cell car from General Motors is that all the propulsion and control systems are in a skateboardlike chassis, maximizing the interior space.

A New Energy Infrastructure

BECAUSE THE U.S. has such rich resources of wind, solar and biomass energy, making large amounts of clean, inexpensive hydrogen will not be so difficult. The bigger problem is logistics: how to deliver hydrogen cheaply to many dispersed sites. The U.S. currently has only about 100 small refueling stations for hydrogen, set up for demonstration purposes. In contrast, the country has 170,000 gasoline stations. These stations cannot be easily converted to hydrogen; the gas is stored and handled differently than liquid fuels such as gasoline, requiring alternative technologies at the pump.

The need for a new infrastructure has created a "chicken and egg" problem for the incipient hydrogen economy. Consumers will not buy hydrogen vehicles unless fuel is widely available at a reasonable price, and fuel suppliers will not build hydrogen stations unless there are enough cars to use them. And although the National Research Council's study projects that hydrogen will become competitive with gasoline once a large distribution system is in place, hydrogen might cost much more during the early years of the transition.

One strategy for jump-starting the changeover is to first

THE AUTHOR

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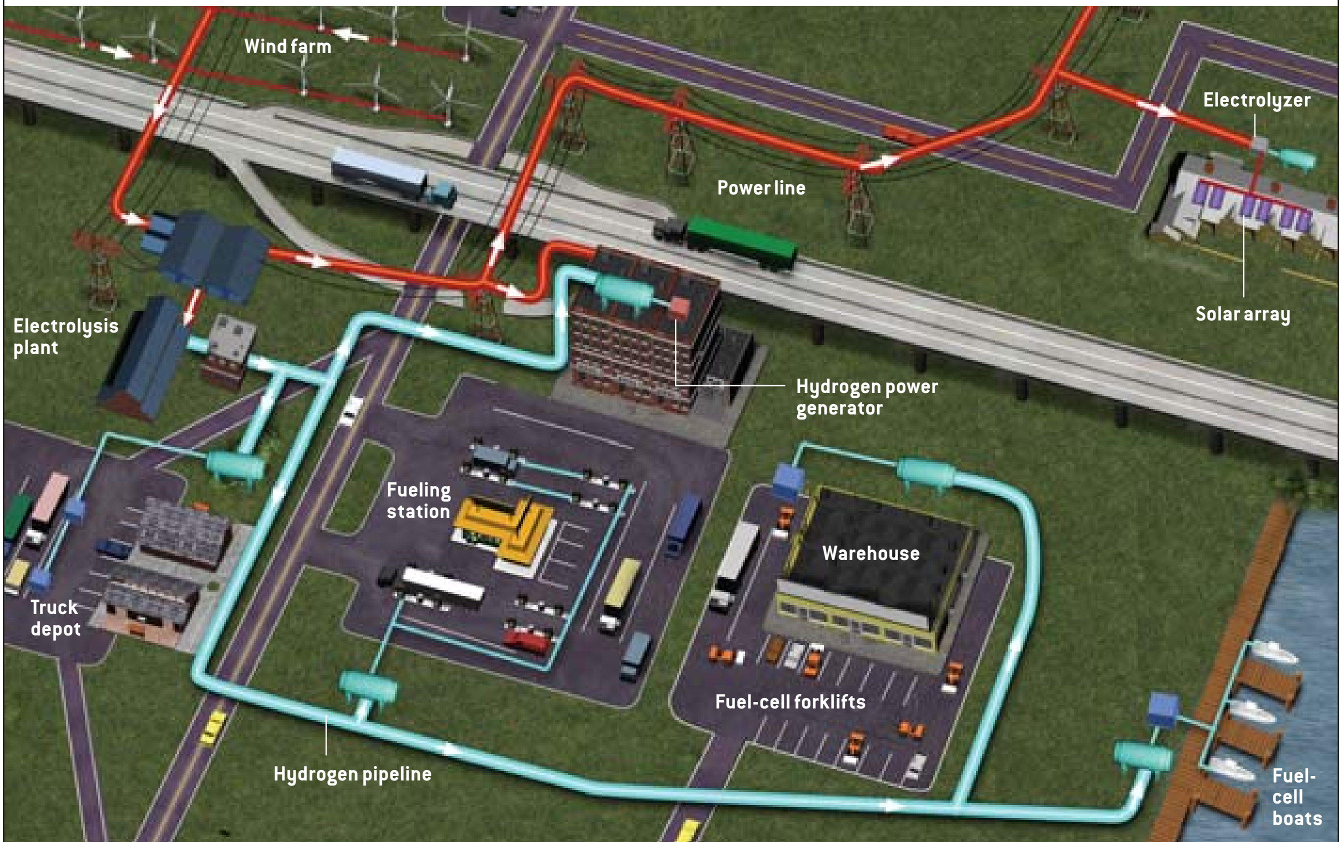
THE MANY USES OF HYDROGEN

Because transporting hydrogen over long distances would be costly, each generation plant would serve the surrounding region. The first users would most likely include fleet vehicles such as trucks and small vehicles that now use electric batteries (for example, forklifts at a warehouse). Hydrogen fuel cells could also power marine engines and provide supplemental electricity for office buildings. The owners of fuel-cell cars could stop at hydrogen stations or even generate their own hydrogen at home using the power from solar arrays.



focus on fleet vehicles—local delivery vans, buses and trucks—that do not require an extensive refueling network. Marine engines and locomotives could also run on hydrogen, which would eliminate significant emissions of air pollutants. Hydrogen fuel cells might power small vehicles that now use electric batteries, such as forklifts, scooters and electric bikes. And fuel cells could also be used in stationary power production: for example, they could generate electricity for police stations, military bases and other customers that do not want to rely solely on the power grid. These niche markets could help bring down the cost of fuel cells and encourage energy companies to build the first commercial hydrogen stations.

To make a substantial dent in global oil use and greenhouse gas emissions, however, hydrogen fuel will have to succeed in passenger vehicle markets. Researchers at the University of California, Davis, have concluded that 5 to 10 percent of urban service stations (plus a few stations connecting cities) must offer hydrogen to give fuel-cell car owners roughly the same convenience enjoyed by gasoline customers. GM has estimated that providing national coverage for the first million hydrogen vehicles in the U.S. would require some 12,000 hydrogen stations in cities and along interstates, each costing about $1 million. Building a full-scale hydrogen system serving 100 million cars in the U.S. might cost several hundred billion dollars, spent over decades. This estimate counts not only the expense of building refueling stations but also the new production and delivery systems that will be needed if hydrogen becomes a popular fuel.

Those numbers may sound daunting, but the World Energy Council projects that the infrastructure costs of maintaining and expanding the North American gasoline economy over the next 30 years will total $1.3 trillion, more than half of which will be spent in oil-producing countries in the developing world. Most of these costs would go toward oil exploration and production. About $300 billion would be for oil refineries, pipelines and tankers—facilities that could eventually be replaced by a hydrogen production and delivery system. Building a hydrogen economy is costly, but so is business as usual.

Furthermore, there are several ways to deliver hydrogen to vehicles. Hydrogen can be produced regionally in large plants, then stored as a liquid or compressed gas, and distributed to

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refueling stations by truck or gas pipeline. It is also possible to make hydrogen locally at stations—or even in homes—from natural gas or electricity [*see box on page 96*]. In the early stages of a hydrogen economy, when the number of fuel-cell vehicles is relatively small, truck delivery or on-site production at refueling stations might be the most economical options. But once a large hydrogen demand is established—say, 25 percent of all the cars in a large city—a regional centralized plant with pipeline delivery offers the lowest cost. Centralized hydrogen production also opens the way for carbon sequestration, which makes sense only at large scales.

In many respects, hydrogen is more like electricity than gasoline. Because hydrogen is more costly to store and transport than gasoline, energy companies will most likely produce the fuel all over the country, with each generation plant serving a regional market. What is more, the supply pathways will vary with location. A hydrogen economy in Ohio—which has plentiful coal and many suitable sites for carbon dioxide sequestration—might look entirely different from one in the Pacific Northwest (which has low-cost hydropower) or one in the Midwest (which can rely on wind power and biofuels). A small town or rural area might rely on truck delivery or on-site production, whereas a large, densely populated city might use a pipeline network to transport hydrogen.

Developing a hydrogen economy will certainly entail some financial risks. If an energy company builds giant production or distribution facilities and the fuel-cell market grows more slowly than expected, the company may not be able to recoup its investments. This dilemma is sometimes called the "stranded asset" problem. The energy industry can minimize its risk, though, by adding hydrogen supply in small increments that closely follow demand. For example, companies could build power plants that generate both electricity and a small stream of hydrogen for the early fuel-cell cars. To distribute the hydrogen, the companies could initially use truck delivery and defer big investments such as pipelines until a large, established demand is in place.

The First Steps

THE ROAD TO a hydrogen transportation system actually consists of several parallel tracks. Raising fuel economy is the essential first step. Developing lightweight cars, more efficient engines and hybrid electric drivetrains can greatly reduce carbon emissions and oil use over the next few decades. Hydrogen and fuel cells will build on this technical progression, taking advantage of the efficiency improvements and the increasing electrification of the vehicles.

The development of the hydrogen fuel infrastructure will be a decades-long process moving in concert with the growing market for fuel-cell vehicles. Through projects such as the California Hydrogen Highways Network and HyWays in Europe, energy companies are already providing hydrogen to test fleets and demonstrating refueling technologies. To enable fuel-cell vehicles to enter mass markets in 10 to 15 years, hydrogen fuel must be widely available at a competitive price by then. Concentrating hydrogen projects in key regions such as southern California or the Northeast corridor might help hasten the growth of the fuel-cell market and reduce the cost of infrastructure investments.

In the near term, the bulk of the hydrogen fuel will most likely be extracted from natural gas. Fueling vehicles this way will cut greenhouse gas emissions only modestly compared with driving gasoline hybrids; to realize hydrogen's full benefits, energy companies must either make the gas from zero-carbon energy sources or sequester the carbon by-products. Once hydrogen becomes a major fuel—say, in 2025 or beyond—governments should phase in requirements for zero or near-zero emissions in its production. And in the meantime, policymakers should encourage the ongoing efforts to develop clean-power technologies such as wind, solar, biomass gasification and carbon sequestration. The shift to a hydrogen economy can be seen as part of a broader move toward lower-carbon energy.

Although the transition may take several decades, hydrogen fuel-cell vehicles could eventually help protect the global climate and reduce America's reliance on foreign oil. The vast potential of this new industry underscores the importance of researching, developing and demonstrating hydrogen technologies now, so they will be ready when we need them. SA

Building a hydrogen economy is costly, but so is business as usual.

MORE TO EXPLORE

The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Research Council and the National Academy of Engineering. National Academies Press, 2004. Available online at www.nap.edu/catalog.php?record_id=10922#toc

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The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate. Joseph J. Romm. Island Press, 2005.

More information about hydrogen fuel-cell technologies and demonstration programs can be found online at http://hydrogen.its.ucdavis.edu/, www1.eere.energy.gov/hydrogenandfuelcells/, www.h2mobility.org/index.html and www.iphe.net/NewAtlas/atlas.htm

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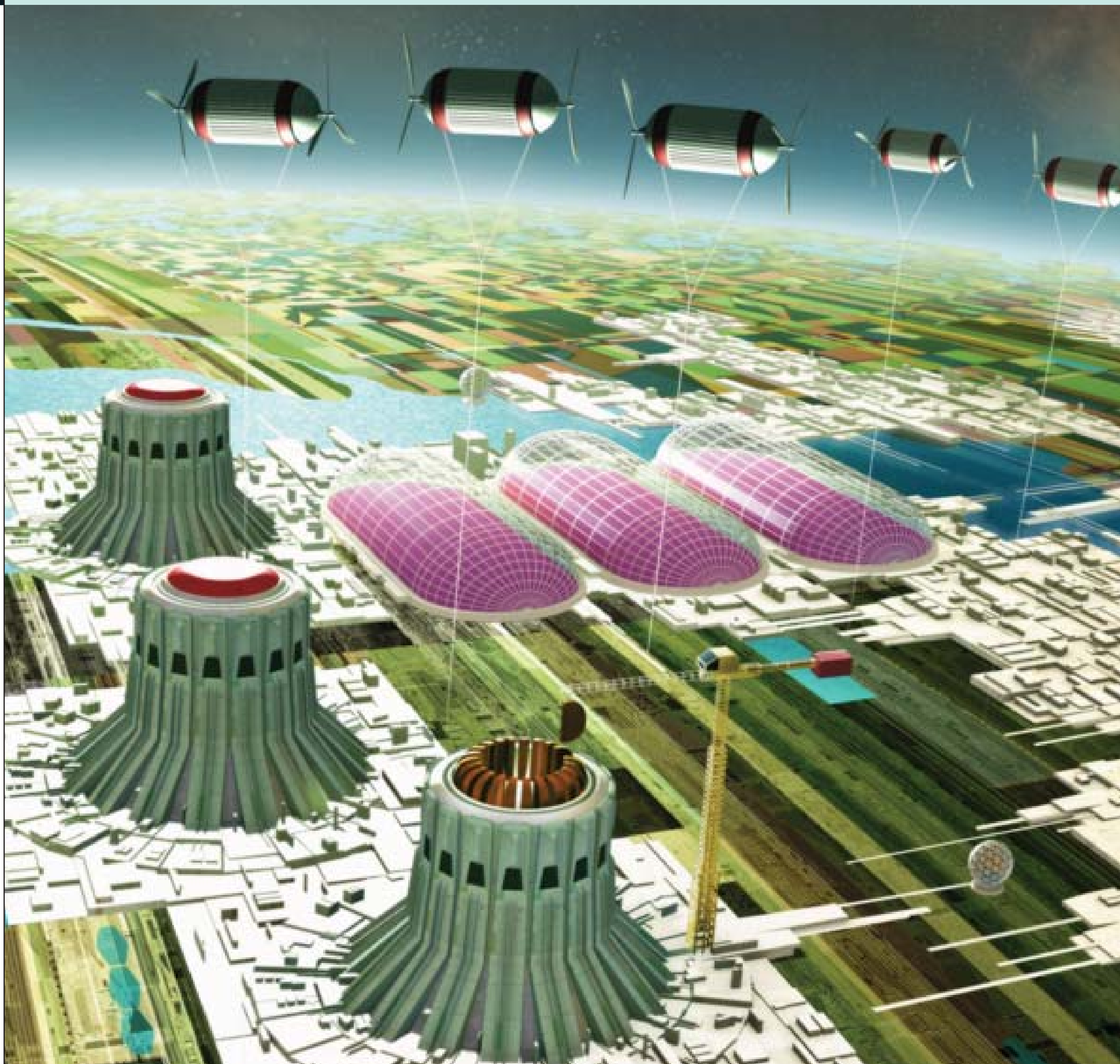

KENN BROWN

OVERVIEW

- Ambitious new technologies could help quench the world's thirst for energy without worsening global climate change.
- Technologies such as these will eventually be called on to slash carbon dioxide production rates, but they may be needed even sooner if conventional approaches restrain CO_2 emissions less than is hoped.

Plan *B* for Energy

If efficiency improvements and incremental advances in today's technologies fail to halt global warming, could revolutionary new carbon-free energy sources save the day? Don't count on it—but don't count it out, either **BY W. WAYT GIBBS**

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▲ Late 21st-century energy sources might include nuclear fusion reactors, hydrogen emitted from ponds of genetically engineered microbes, high-altitude wind farms, orbiting solar arrays, and wave and tidal generators—all linked to a worldwide superconducting grid.

To keep this world tolerable for life as we like it, humanity must complete a marathon of technological change whose finish line lies far over the horizon. Robert H. Socolow and Stephen W. Pacala of Princeton University have compared the feat to a multigenerational relay race [see their article "A Plan to Keep Carbon in Check," on page 50]. They outline a strategy to win the first 50-year leg by reining back carbon dioxide emissions from a century of unbridled acceleration. Existing technologies, applied both wisely and promptly, should carry us to this first milestone without trampling the global economy. That is a sound plan A.

The plan is far from foolproof, however. It depends on societies ramping up an array of carbon-reducing practices to form seven "wedges," each of which keeps 25 billion tons of carbon in the ground and out of the air. Any slow starts or early plateaus will pull us off track. And some scientists worry that stabilizing greenhouse gas emissions will require up to 18 wedges by 2056, not the seven that Socolow and Pacala forecast in their most widely cited model [*see box on next page*].

It is a mistake to assume that carbon releases will rise more slowly than will economic output and energy use, argues Martin I. Hoffert, a physicist at New York University. As oil and gas prices rise, he notes, the energy industry is "re-

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carbonizing" by turning back to coal. "About 850 coal-fired power plants are slated to be built by the U.S., China and India—none of which signed the Kyoto Protocol," Hoffert says. "By 2012 the emissions of those plants will overwhelm Kyoto reductions by a factor of five."

Even if plan A works and the teenagers of today complete the first leg of the relay by the time they retire, the race will be but half won. The baton will then pass in 2056 to a new generation for the next and possibly harder part of the marathon: cutting the rate of CO_2 emissions in half by 2106.

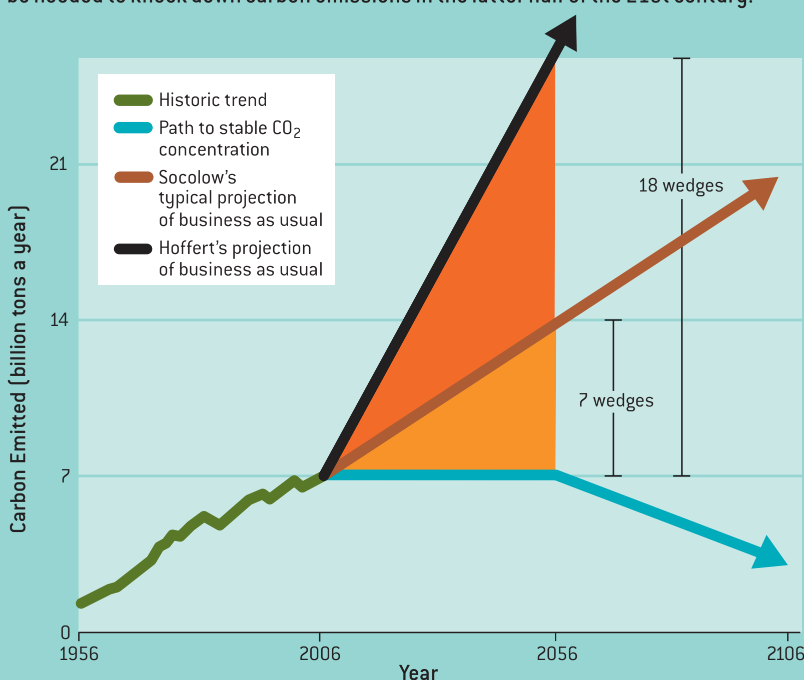
Sooner or later the world is thus going to need a plan B: one or more fundamentally new technologies that together can supply 10 to 30 terawatts without belching a single ton of carbon dioxide. Energy buffs have been kicking around many such wild ideas since the 1960s. It is time to get serious about them. "If we don't start now building the infrastructure for a revolutionary change in the energy system," Hoffert warns, "we'll never be able to do it in time."

But what to build? The survey that follows sizes up some of the most promising options, as well as a couple that are popular yet implausible. None of them is a sure thing. But from one of these ideas might emerge a new engine of human civilization.

PLAN B: SOONER—OR LATER?

Staving off catastrophic global warming means bridging a gap between the amount of carbon emitted by business as usual and a flat path toward a stable carbon dioxide concentration. That gap may grow much more rapidly than Robert H. Socolow of Princeton and many economists typically estimate, warns N.Y.U. physicist Martin I. Hoffert. The standard "seven wedge" scenario [*see box on page 54*] assumes that both the energy consumed per dollar of GDP and the carbon emitted per kilowatt of energy will continue to fall. Hoffert points out, however, that China and India have begun "recarbonizing," emitting more CO_2 per kilowatt every year as they build coal-fired plants. Carbon-to-energy ratios have stopped falling in the U.S. as well. Socolow acknowledges that the seven-wedge projection assumes substantial advances in efficiency and renewable energy production as part of business as usual.

Even if those assumptions all prove correct, revolutionary technologies will still be needed to knock down carbon emissions in the latter half of the 21st century.



JEN CHRISTIANSEN; SOURCES: ROBERT H. SOCOLOW AND MARTIN I. HOFFERT

NUCLEAR FUSION

Starry-eyed physicists point to the promise of unlimited fuel and minimal waste. But politicians blanch at fusion's price tag and worry about getting burned

Fusion reactors—which make nuclear power by joining atoms rather than splitting them—top almost everyone's list of ultimate energy technologies for humanity. By harnessing the same strong thermonuclear force that fires the sun, a fusion plant could extract a gigawatt of electricity from just a few kilograms of fuel a day. Its hydrogen-isotope fuel would come from seawater and lithium, a common metal. The reactor would produce no greenhouse gases and relatively small amounts of low-level radioactive waste, which would become harmless within a century. "Even if the plant were flattened [by an accident or attack], the radiation level one kilometer outside the fence would be so small that evacuation would not be necessary," says Farrokh Najmabadi, a fusion expert who directs the Center for Energy Research at the University of California, San Diego.

The question is whether fusion can make a large contribution to the 21st century or is a 22nd-century solution. "A decade ago some scientists questioned whether fusion was possible, even in the lab," says David E. Baldwin, who as head of the energy group at General Atomics oversees the largest fusion reactor in the U.S., the DIII-D. But the past 20 years have seen dramatic improvements in tokamaks, machines that use giant electromagnetic coils to confine the ionized fuel within a doughnut-shaped chamber as it heats the plasma to more than 100 million degrees Celsius.

"We now know that fusion will work," Baldwin says. "The question is whether it is economically practical"—and if so, how quickly fusion could move from its current experimental form into large-scale commercial reactors. "Even with a crash program," he says, "I think we would need 25 to 30 years" to develop such a design.

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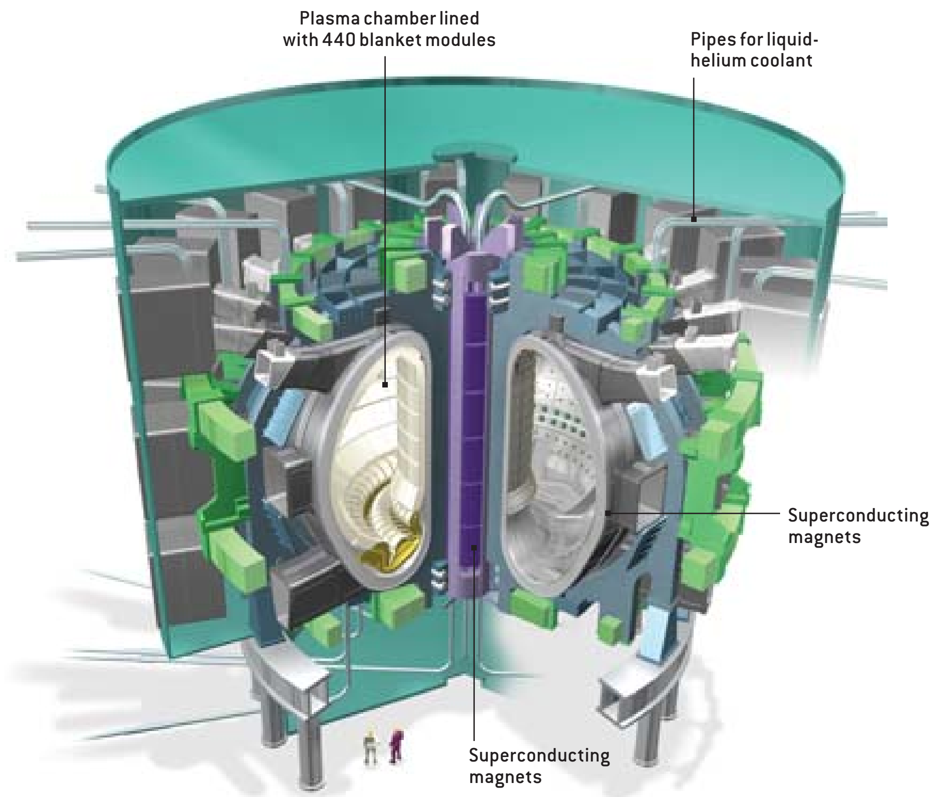
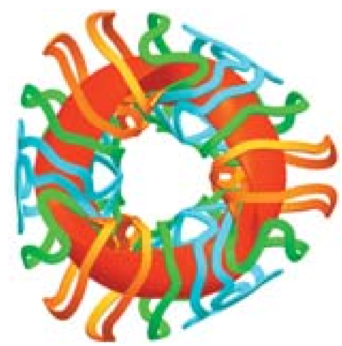


◀ ITER fusion reactor will be the first tokamak to generate far more energy than it consumes, once operations begin in the latter part of the next decade. Fusion experts are already planning a successor reactor, called DEMO—the first commercially viable electricity plant to run on the power source of the stars.



▲ Stellarators work much like tokamaks but use more complex magnet shapes that make it easier to confine the superhot plasma (*orange*). The ARIES working group is analyzing reference designs for a commercial-scale stellarator.

© 2006 ERIC VERDULT, WWW.KENNISINBEELD.NL (*left*); ARIES PROGRAM, UNIVERSITY OF CALIFORNIA, SAN DIEGO (*right*)

So far political leaders have chosen to push fusion along much more slowly. Nearly 20 years after it was first proposed, the International Thermonuclear Experimental Reactor (ITER) is only now nearing final approval. If construction begins on schedule next year, the $10-billion reactor should begin operation in southeastern France in 2016.

Meanwhile an intermediate generation of tokamaks now nearing completion in India, China and Korea will test whether coils made of superconducting materials can swirl the burning plasma within its magnetic bottle for minutes at a time. Current reactors manage a few dozen seconds at best before their power supplies give out.

ITER aims for three principal goals. First it must demonstrate that a large tokamak can control the fusion of the hydrogen isotopes deuterium and tritium into helium long enough to generate 10 times the energy it consumes. A secondary aim is to test ways to use the high-speed neutrons created by the reaction to breed tritium fuel—for example, by shooting them into a surrounding blanket of lithium. The third goal is to integrate the wide range of technologies needed for a commercial fusion plant.

If ITER succeeds, it will not add a single watt to the grid. But it will carry fusion past a milestone that nuclear fission energy reached in 1942, when Enrico Fermi oversaw the first self-sustaining nuclear chain reaction. Fission reactors were powering submarines 11 years later. Fusion is an incomparably harder problem, however, and some veterans in the field predict that 20 to 30 years of experiments with ITER will be needed to refine designs for a production plant.

Najmabadi is more optimistic. He leads a working group that has already produced three rough designs for commercial fusion reactors. The latest, called ARIES-AT, would have a more compact footprint—and thus a lower capital cost—than ITER. The ARIES-AT machine would produce 1,000 megawatts at a price of roughly five cents per kilowatt-hour, competitive with today's oil- and gas-fired plants. If work on a commercial plant began in parallel with ITER, rather than decades after it goes online, fusion might be ready to scale up for production by midcentury, Najmabadi argues.

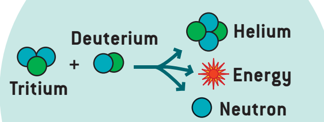
Fusion would be even more cost-competitive, Hoffert suggests, if the fast neutrons produced by tokamaks were used to transmute thorium (which is relatively abundant) into uranium (which may be scarce 50 years hence) to use as fuel in nuclear fission plants. "Fusion advocates don't want to sully its clean image," Hoffert observes, "but fusion-fission hybrids may be the way to go."

REALITY FACTOR 3*

** Estimated technical feasibility from 1 (implausible) to 5 (ready for market)*

Fast Facts

Fusion Reaction



Next-Generation Fusion Reactors

Project	Place	Online
EAST	China	2006
SST-1	India	2006
K-Star	Korea	2008
NIF	U.S.	2009
ITER	France	2016
NCT	Japan	?

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HIGH-ALTITUDE WIND

The most energetic gales soar far over the tops of today's turbines. New designs would rise higher—perhaps even to the jet stream

Wind is solar energy in motion. About 0.5 percent of the sunlight entering the atmosphere is transmuted into the kinetic energy of air: a mere 1.7 watts, on average, in the atmospheric column above every square meter of the earth. Fortunately, that energy is not distributed evenly but concentrated into strong currents. Unfortunately, the largest, most powerful and most consistent currents are all at high altitude. Hoffert estimates that roughly two thirds of the total wind energy on this planet resides in the upper troposphere, beyond the reach of today's wind farms.

Ken Caldeira of the Carnegie Institution of Washington once calculated how wind power varies with altitude, latitude and season. The mother lode is the jet stream, about 10,000 meters (33,000 feet) up between 20 and 40 degrees latitude in the Northern Hemisphere. In the skies over the U.S., Europe, China and Japan—indeed, many of the countries best prepared to exploit it—wind power surges to 5,000 or even 10,000 watts a square meter. The jet stream does wander. But it never stops.

If wind is ever to contribute terawatts to the global energy budget, engineers will have to invent affordable ways to mine the mother lode. Three high-flying designs are in active development.

Magenn Power in Ottawa, Ontario, plans to begin selling next year a rotating, helium-filled generator that exploits the Magnus effect (best known for giving loft to spinning golf balls) to float on a tether up to 122 meters above the ground. The bus-size device will produce four kilowatts at its ground station and will retail for about $10,000—helium not included. The company aims to produce higher-flying, 1.6-megawatt units, each the size of a football field, by 2010.

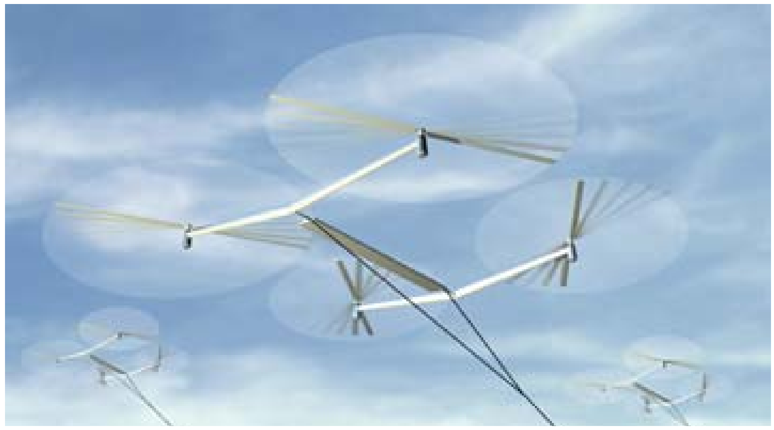
"We looked at balloons; the drag they produce seemed unmanageable in high winds," says Al Grenier of Sky WindPower in Ramona, Calif. Grenier's venture is instead pursuing autogiros, which catch the wind with helicopterlike rotors. Rising to 10,000 meters, the machines could realize 90 percent of their peak capacity. The inconstancy of surface winds limits ground turbines to about half that. But the company has struggled to gather the $4 million it needs for a 250-kilowatt prototype.

Still in the conceptual stages is the "laddermill," designed by astronaut Wubbo J. Ockels and his students at the Delft University of Technology in the Netherlands. Ockels envisions a series of computer-controlled kites connected by a long tether. The ladder of kites rises and descends, turning a generator on the ground as it yo-yos up and down. Simulations of the system suggest that a single laddermill reaching to the jet stream could produce up to 50 megawatts of energy.

Until high-altitude machines are fielded, no one can be certain how well they will hold up under turbulence, gusts and lightning strikes. Steep maintenance costs could be their downfall.

There are regulatory hurdles to clear as well. Airborne wind farms need less land than their terrestrial counterparts, but their operators must persuade national aviation agencies to restrict aircraft traffic in the vicinity. There is precedent for this, Grenier points out: the U.S. Air Force has for years flown up to a dozen large tethered aerostats at high altitude above the country's southern border.

By the standards of revolutionary technologies, however, high-altitude wind looks relatively straightforward and benign.

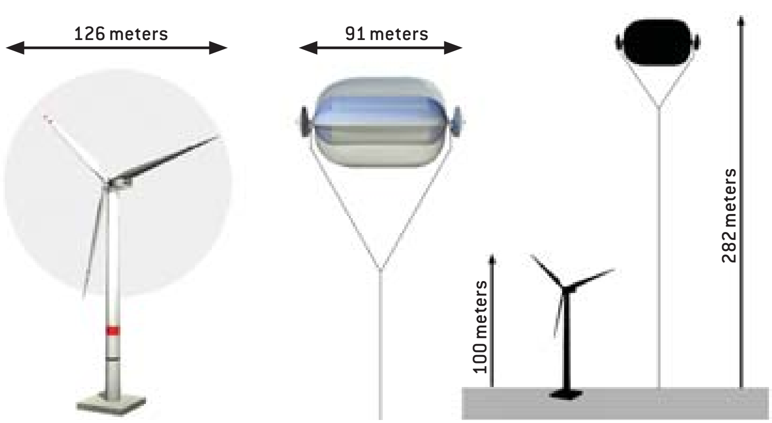


▲ Autogiros designed by Sky WindPower would use powered counterrotating blades to rise above 10,000 feet, then switch to generating mode. Computers adjust the pitch of the four blades to maintain the craft's position and attitude.

Fast Facts

- Wind power capacity, currently about 58 gigawatts, is expected to triple by 2014.
- Helium-filled generators have to be refilled every few months.
- Number of tethered aerostats monitoring the U.S. border: 8.

REALITY FACTOR 4



▲ Floating wind generators planned for 2010 production by Magenn Power would rise nearly twice as high as the largest turbines today but would be about two thirds as wide.

DON FOLEY; SOURCES: BEN SHEPARD *Sky WindPower Corporation* (*top*); MAGENN POWER (*bottom*)

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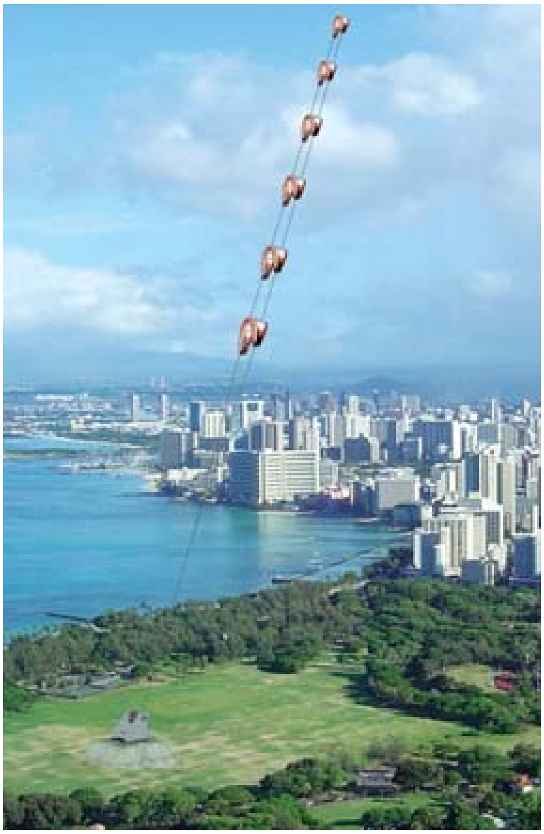
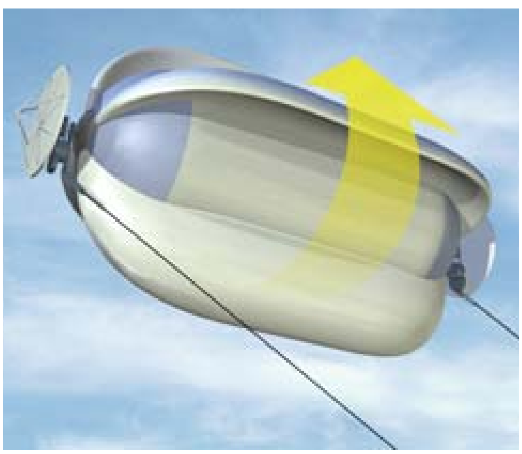


▲ Laddermill wind power system would string C-shaped kites (*shown*), parasails or flying wings along the upper half of a wire. Each wing would use sensors and actuators for steering and pitch control as it climbed and then descended. The scheme would allow heavy generators to remain on the ground.



▲ Like a spinning blimp, a helium-filled rotor would catch the wind in fabric scoops, turning generators attached to tethers, which would then conduct the electricity to a transformer on the ground.

ASSET *Delft University of Technology* (*top left*); DON FOLEY (*bottom left*); GETTY IMAGES (*top right*); © PARAMOUNT TELEVISION/COURTESY OF EVERETT COLLECTION (*bottom right*)

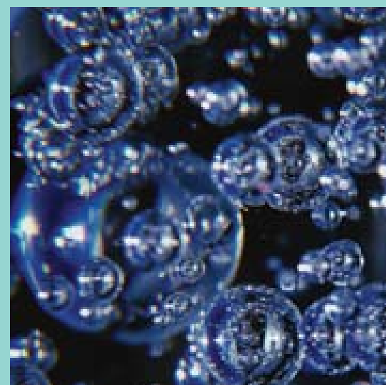
SCI-FI SOLUTIONS

Futuristic visions make for great entertainment. Too bad about the physics

REALITY FACTOR 1

Cold Fusion and Bubble Fusion

B. Stanley Pons and Martin Fleischmann spun a tempest in a teacup in 1989 with their claim of room-temperature fusion in a bottle. The idea drew a coterie of die-hard supporters, but mainstream scientists have roundly rejected that variety of cold fusion.



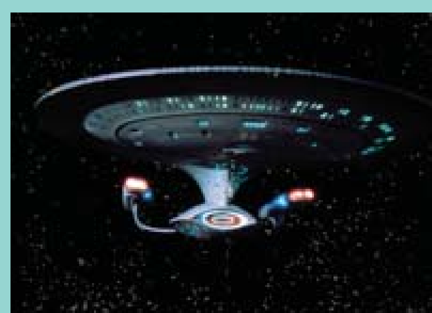
▲ The bubbles keep bursting.

Theoretically more plausible—but still experimentally contentious—is sonofusion. In 2002 Rusi Taleyarkhan, a physicist then at Oak Ridge National Laboratory, reported in *Science* that beaming high-intensity ultrasound and neutrons into a vat of acetone caused microscopic bubbles to form and then implode at hypersonic speeds. The acetone had been made using deuterium, a neutron-bearing form of hydrogen, and Taleyarkhan's group claimed that the extraordinary temperatures and pressures created inside the imploding bubbles forced a few deuterium atoms to fuse with incoming neutrons to form tritium (hydrogen with two neutrons per atom). Another group at Oak Ridge replicated the experiment but saw no clear signs of fusion.

Taleyarkhan moved to Purdue University and continued reporting success with sonic fusion even as others tried but failed. Purdue this year investigated allegations that Taleyarkhan had interfered with colleagues whose work seemed to contradict his own. The results of the inquiry were sealed—and with them another chapter in the disappointing history of cold fusion. Other researchers hold out hope that different methods might someday turn a new page on sonofusion.

Matter-Antimatter Reactors

The storied *Enterprise* starships fueled their warp drives with a mix of matter and antimatter; why can't we? The combination is undoubtedly powerful: a kilogram of each would, through their mutual annihilation, release about half as much energy as all the gasoline burned in the U.S. last year. But there are no known natural sources of antimatter, so we would have to synthesize it. And the most efficient antimatter maker in the world, the particle accelerator at CERN near Geneva, would have to run nonstop for 100 trillion years to make a kilogram of antiprotons.



▲ A warped vision of reality.

So even though physicists have ways to capture the odd antiatom [see "Making Cold Antimatter," by Graham P. Collins; Scientific American, June 2005], antimatter power plants will never materialize.

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SPACE-BASED SOLAR

With panels in orbit, where the sun shines brightest— and all the time—solar could really take off. But there's a catch

When Peter Glaser proposed in 1968 that city-size satellites could harvest solar power from deep space and beam it back to the earth as invisible microwaves, the idea seemed pretty far out, even given Glaser's credentials as president of the International Solar Energy Society. But after the oil crises of the 1970s sent fuel prices skyrocketing, NASA engineers gave the scheme a long hard look. The technology seemed feasible until, in 1979, they estimated the "cost to first power": $305 billion (in 2000 dollars). That was the end of that project.

Solar and space technologies have made great strides since then, however, and space solar power (SSP) still has its champions. Hoffert cites two big advantages that high-flying arrays could lord over their earthbound brethren. In a geostationary orbit well clear of the earth's shadow and atmosphere, the average intensity of sunshine is eight times as strong as it is on the ground. And with the sun always in their sights, SSP stations could feed a reliable, fixed amount of electricity into the grid. (A rectifying antenna, or "rectenna," spread over several square kilometers of land could convert microwaves to electric current with about 90 percent efficiency, even when obstructed by clouds.)

"SSP offers a truly sustainable, global-scale and emission-free electricity source," Hoffert argues. "It is more cost-effective and more technologically feasible than controlled thermonuclear fusion." Yet there is minimal research funding for space-based solar, he complains, while a $10-billion fusion reactor has just been approved.

NASA did in fact fund small studies from 1995 to 2003 that evaluated a variety of SSP components and architectures. The designs took advantage of thin-film photovoltaics to create the electricity, high-temperature superconductors to carry it, and infrared lasers (in place of microwave emitters) to beam it to ground stations. Such high-tech innovations enabled SSP engineers to cut the systems' weight and thus reduce the formidable cost of launching them into orbit.

But here's the catch: the power-to-payload ratio, at a few hundred watts per kilogram, has remained far too low. Until it rises, space-based solar will never match the price of other renewable energy sources, even accounting for the energy storage systems that ground-based alternatives require to smooth over nighttime and poor-weather lulls.

Technical advances could change the game rapidly, however. Lighter or more efficient photovoltaic materials are in the works [see "Nanotech Solar Cells," on page 110]. In May, for example, researchers at the University of Neuchâtel in Switzerland reported a new technique for depositing amorphous silicon cells on a space-hardy film that yields power densities of 3,200 watts per kilogram. Although that is encouraging, says John C. Mankins, who led NASA's SSP program from 1995 to 2003, "the devil is in the supporting structure and power management." Mankins sees more promise in advanced earth-to-orbit space transportation systems, now on drawing boards, that might cut launch costs from more than $10,000 a kilogram to a few hundred dollars in coming decades.

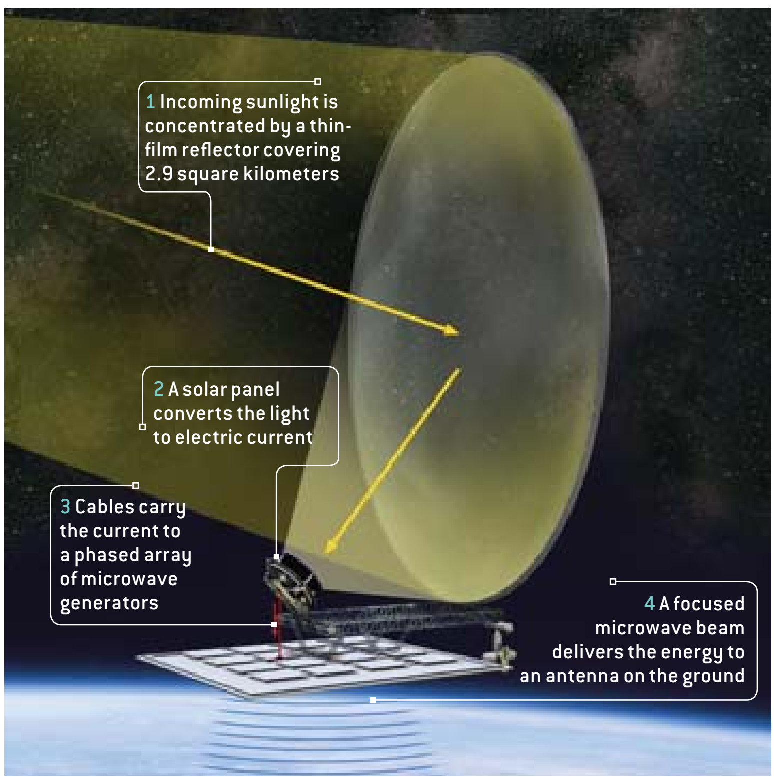
JAXA, the Japanese space agency, last year announced plans to launch by 2010 a satellite that will unfurl a large solar array and beam 100 kilowatts of microwave or laser power to a receiving station on the earth. The agency's long-term road map calls for flying a 250-megawatt prototype system by 2020 in preparation for a gigawatt-class commercial SSP plant a decade later.

NASA once had similarly grand designs, but the agency largely halted work on SSP when its priorities shifted to space exploration two years ago.

Showstoppers

- Large teams of robots will have to work together to assemble the giant arrays.
- The microwave beams could cause interference with communications systems.
- Space agencies will have to boost their launch rates by a factor of about 80.
- Rectennas will occupy large swaths of land.

REALITY FACTOR 3



▲ Giant solar collector in geosynchronous orbit would work day and night, in any weather. A pilot plant of the size above would intercept four gigawatts of sunlight, convert it to 1.8 GW of microwaves, and deliver 1.1 GW of electricity to the grid.

DON FOLEY

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NANOTECH SOLAR CELLS

Materials engineered from the atoms up could boost photovoltaic efficiencies from pathetic to profitable

Five gigawatts—a paltry 0.038 percent of the world's consumption of energy from all sources. That, roughly, is the cumulative capacity of all photovoltaic (PV) power systems installed in the world, half a century after solar cells were first commercialized. In the category of greatest unfulfilled potential, solar-electric power is a technology without rival.

Even if orbiting arrays [see "Space-Based Solar," on page 108] never get off the ground, nanotechnology now looks set to rescue solar from its perennial irrelevance, however. Engineers are working on a wide range of materials that outshine the bulk silicon used in most PV cells today, improving both their efficiency and their cost.

The most sophisticated (and expensive) second-generation silicon cells eke out about 22 percent efficiency. New materials laced with quantum dots might double that, if discoveries reported this past March pan out as hoped. The dots, each less than 10 billionths of a meter wide, were created by groups at the National Renewable Energy Laboratory in Colorado and Los Alamos National Laboratory in New Mexico.

When sunlight hits a silicon cell, most of it ends up as heat. At best, a photon can knock loose one electron. Quantum dots can put a wider range of wavelengths to useful work and can kick out as many as seven electrons for every photon. Most of those electrons soon get stuck again, so engineers are testing better ways to funnel them into wires. They are also hunting for dot materials that are more environmentally friendly than the lead, selenium and cadmium in today's nanocrystals. Despite their high-tech name, the dots are relatively inexpensive to make.

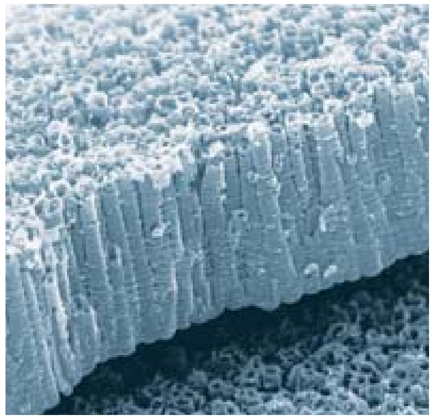
Nanoparticles of a different kind promise to help solar compete on price. Near San Francisco, Nanosolar is building a factory that will churn out 200 million cells a year by printing nanoscopic bits of copper-indium-gallium-diselenide onto continuous reels of ultrathin film. The particles self-assemble into light-harvesting structures. Nanosolar's CEO says he is aiming to bring the cost down to 50 cents a watt.

The buzz has awakened energy giants. Shell now has a subsidiary making solar cells, and BP in June launched a five-year project with the California Institute of Technology. Its goal: high-efficiency solar cells made from silicon nanorods.

Essentials

50¢: the price to beat for a one-watt solar cell

REALITY FACTOR 4



▲ Titania nanotubes made at Pennsylvania State University boost the light-harvesting abilities of solar cell dyes 10-fold.

A GLOBAL SUPERGRID

Revolutionary energy sources need a revolutionary superconducting electrical grid that spans the planet

"A basic problem with renewable energy sources is matching supply and demand," Hoffert observes. Supplies of sunshine, wind, waves and even biofuel crops fade in and out unpredictably, and they tend to be concentrated where people are not. One solution is to build long-distance transmission lines from superconducting wires. When chilled to near absolute zero, these conduits can wheel tremendous currents over vast distances with almost no loss.

In July the BOC Group in New Jersey and its partners began installing 350 meters of superconducting cable into the grid in Albany, N.Y. The nitrogen-cooled link will carry up to 48 megawatts' worth of current at 34,500 volts. "We know the technology works; this project will demonstrate that," says Ed Garcia, a vice president at BOC.

At a 2004 workshop, experts sketched out designs for a "SuperGrid" that would simultaneously transport electricity and hydrogen. The hydrogen, condensed to a liquid or ultracold gas, would cool the superconducting wires and could also power fuel cells and combustion engines [see "A Power Grid for the Hydrogen Economy," by Paul M. Grant, Chauncey Starr and Thomas J. Overbye; SCIENTIFIC AMERICAN, July].

With a transcontinental SuperGrid, solar arrays in Australia and wind farms in Siberia might power lights in the U.S. and air conditioners in Europe. But building such infrastructure would most likely take generations and trillions of dollars.

▲ Global grid route proposed in 1981 by Buckminster Fuller connects every populated continent but avoids long ocean crossings.

REALITY FACTOR 2

MAGGIE PAULOSE *Pennsylvania State University* (*top*); LUCY READING-IKKANDA (*bottom*)

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WAVES AND TIDES

The surging ocean offers a huge, but virtually untapped, energy resource. Companies are now gearing up to catch the wave

In Progress

Tidal and Wave Energy Projects

- Rhode Island: 500 kW in 2006
- Northern Ireland: 1 MW in late 2006
- Cantabria, Spain: 1.25 MW by 2007
- Northern Portugal: 24 MW by 2007
- Cornwall, England: 5 MW by 2008
- Northern Devon, England: 10 MW by 2010
- Daishan, China: 120 to 150 kW; no date announced

REALITY FACTOR
5

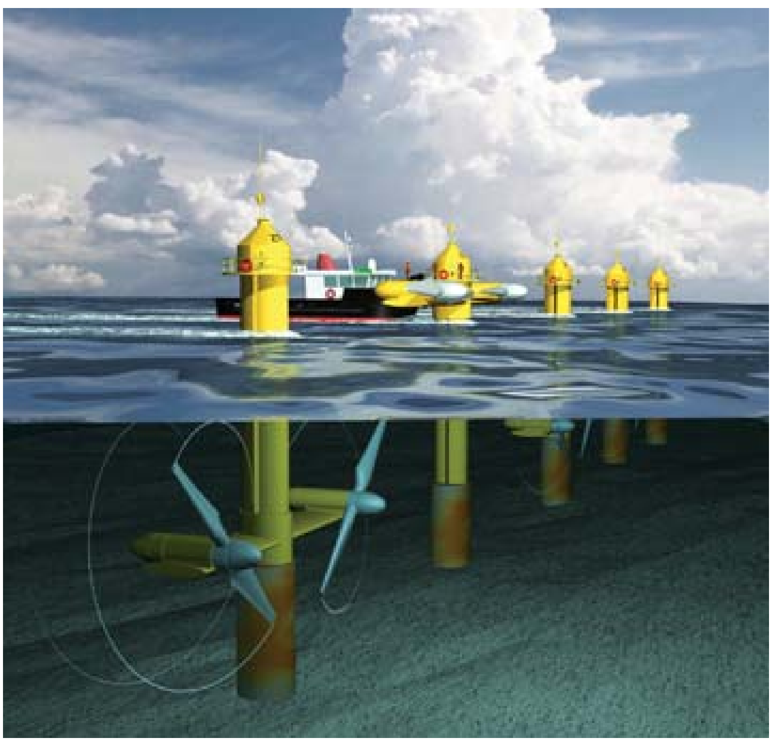
The tide has clearly turned for the dream of harnessing the incessant motion of the sea. "Ocean energy is about 20 years behind wind power," acknowledges Roger Bedard, ocean energy leader at the Electric Power Research Institute. "But it certainly isn't going to take 20 years to catch up."

Through the 1980s and 1990s, advocates of tidal and wave power could point to only two commercial successes: a 240-megawatt (MW) tidal plant in France and a 20-MW tidal station in Nova Scotia. Now China has jumped onboard with a 40-kilowatt (kW) facility in Daishan. Six 36-kW turbines are soon to start spinning in New York City's East River. This summer the first commercial wave farm will go online in Portugal. And investors and governments are hatching much grander schemes.

The grandest is in Britain, where analysts suggest ocean power could eventually supply one fifth of the country's electricity and fulfill its obligations under the Kyoto Protocol. The U.K. government in July ordered a feasibility study for a 16-kilometer dam across the Severn estuary, whose tides rank second largest in the world. The Severn barrage, as it is called, would cost $25 billion and produce 8.6 gigawatts when tides were flowing. Proponents claim it would operate for a century or more.

▲ Wave energy devices made by Ocean Power Delivery derive electrical power from the flexing motion at their joints as waves pass underneath. Because they dive into oncoming waves, the Pelamis machines can survive the high seas that accompany intense storms.

▼ Tide farm planned by Marine Current Turbines would use an array of turbines spaced more closely than wind generators are. The rotors, each up to 20 meters in diameter, drop to sap energy from tidal currents but can surface for servicing.



Environmental groups warn that the barrage would wreak havoc on the estuarine ecosystem. Better than a dam, argues Peter Fraenkel of Marine Current Turbines, would be arrays of the SeaGen turbines his company has developed. Such tide farms dotting the U.K. coast could generate almost as much electricity as the Severn dam but with less capital investment, power variation and environmental impact.

Fraenkel's claims will be put to a small test this year, when a tidal generator the company is installing in Strangford Lough begins contributing an average power of 540 kW to the grid in Northern Ireland. The machine works much like an underwater windmill, with two rotors sharing a single mast cemented into the seabed.

"The biggest advantage of tidal power is that it is completely predictable," Bedard says. "But on a global scale, it will never be very large." There are too few places where tides move fast enough.

Energetic waves are more capricious but also more ubiquitous. An analysis by Bedard's group found that if just 20 percent of the commercially viable offshore wave resources in the U.S. were harnessed with 50-percent-efficient wave farms, the energy produced would exceed all conventional hydroelectric generation in the country.

Four companies have recently completed sea trials of their wave conversion designs. One of them, Ocean Power Delivery, will soon begin reaping 2.25 MW off the coast of Portugal from three of its 120-meter-long Pelamis machines. If all goes well, it will order another 30 this year. Surf's up.

OCEAN POWER DELIVERY (*top*); MARINE CURRENT TURBINES TM LTD. (*bottom*)

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DESIGNER MICROBES

Genetic engineers think they can create synthetic life-forms that will let us grow energy as easily as we do food

"We view the genome as the software, or even the operating system, of the cell," said J. Craig Venter. It's time for an upgrade, he suggested. Venter was preaching to the choir: a large group of biologists at the Synthetic Biology 2.0 conference this past May. Many of the scientists there have projects to genetically rewire organisms so extensively that the resulting cells would qualify as synthetic species. Venter, who gained fame and fortune for the high-speed methods he helped to develop to sequence the human genome, recently founded a company, Synthetic Genomics, to commercialize custom-built cells. "We think this field has tremendous potential to replace the petrochemical industry, possibly within a decade," he said.

That assessment may be overly optimistic; no one has yet assembled a single cell from scratch. But Venter reported rapid progress on his team's efforts to create artificial chromosomes that contain just the minimum set of genes required for self-sustaining life within a controlled, nutrient-rich environment. "The first synthetic prokaryotic cell [lacking a nucleus] will definitely happen within the next two years," he predicted. "And synthetic eukaryotic genomes [for cells with nuclei] will happen within a decade at most."

Venter envisions novel microbes that capture carbon dioxide from the smokestack of a power plant and turn it into natural gas for the boiler. "There are already thousands, perhaps millions, of organisms on our planet that know how to do this," Venter said. Although none of those species may be suited for life in a power plant, engineers could borrow their genetic circuits for new creations. "We also have biological systems under construction that are trying to produce hydrogen directly from sunlight, using photosynthesis," he added.

Steven Chu, director of Lawrence Berkeley National Laboratory, announced that his lab is readying a proposal for a major project to harness the power of the sun and turn it into fuels for transportation. With the tools of genetic engineering, Chu explained, "we can work on modifying plants and algaes to make them self-fertilizing and resistant to drought and pests." The novel crops would offer high yields of cellulose, which man-made microbes could then convert to fuels. Chu expects biological processing to be far more efficient than the energy-intensive processes, such as steam explosion and thermal hydrolysis, currently used to make ethanol.

With oil prices approaching $80 a barrel, bioprocessing may not have to wait for life-forms built from scratch. GreenFuel in Cambridge, Mass., has installed algae farms at power plants to convert up to 40 percent of the CO_2 they spew into raw material for biofuels. The company claims that a large algae farm next to a 1-GW plant could yield 50 million gallons a year of ethanol. "There are great opportunities here," Chu avers. "And not only that—it will help save the world." SA

Essentials

5,000: Gallons per acre of biodiesel from a CO_2-fueled algae farm

REALITY FACTOR 4

▲ Greenhouse-covered pools similar to the lake in Biosphere 2 might one day grow novel microorganisms, plants or algaes designed to produce hydrogen, sequester carbon dioxide, or convert crops into fuels.

PETER ESSICK *Aurora/Getty Images*

MORE TO EXPLORE

Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. Martin I. Hoffert et al. in *Science,* Vol. 298, pages 981–987; November 1, 2002.

Proceedings of the Hydrokinetic and Wave Energy Technologies Technical and Environmental Issues Workshop. Washington, D.C., October 26–28, 2005. Available at **http://hydropower.inl.gov/hydrokinetic_wave**

URSI White Paper on Solar Power Satellites. International Union of Radio Science, November 2005. Available at **www.ursi.org**

Engineering Life: Building a Fab for Biology. Bio Fab Group in *Scientific American,* Vol. 294, No. 6, pages 44–51; June 2006.

A video tour of the DIII-D fusion reactor is available at **www.sciam.com/ontheweb**

For more information about the ITER and ARIES fusion reactor projects, see **www.iter.org** and **http://aries.ucsd.edu/ARIES**

Further details about high-altitude wind generators are available at **www.skywindpower.com, www.magenn.com** and **www.lr.tudelft.nl/asset**

A Webcast of the Second International Conference on Synthetic Biology is available at **http://webcast.berkeley.edu/events**

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WORKINGKNOWLEDGE

WATER TOWERS

Tall Task

Drive past a water tower, and it appears to be a silent, passive giant. But it is the central player in a high-pressure balancing act.

Most municipalities obtain their water from a reservoir or well, purify it at a treatment plant and send it to a pump house that fills one or more elevated tanks. The pumps alone are strong enough to push water throughout a town's network of pipes, but the system's pressure—at your sink—would fluctuate as usage rose and fell and could drop too low to reach spigots during high demand. "A water tower acts like a capacitor. It maintains constant pressure on the lines and provides backup supply when demand exceeds pump output," explains Malcolm Jackson, a general manager for Utility Service Company, Inc., in Perry, Ga., which provides tank services nationwide.

A tank is sized to hold about a one-day supply plus reserves, notes Kevin Gallagher, vice president of sales at Caldwell Tanks in Louisville, Ky. Pumps may operate around the clock, filling a tank overnight when demand is low. When most of the population jumps into the shower in the morning, the tank is drawn down to augment what the pumps provide.

Water towers are prominent on flat land, but tanks are everywhere, resting (and often hidden) on high ground in hilly locales and perched on rooftops in cities. A tower or hilltop tank is typically situated 100 feet above the highest users. Each one of those feet creates 0.433 pound per square inch of pressure—43.3 psi for a difference of 100 feet. Pressure in street pipes in a valley far below could rise much higher; towns insert pressure-reduction valves on lines where pressure reaches 80 psi or more, which could damage a building's plumbing seals and valves, notes Anthony O'Malley, principal of the Larkin Group, water engineering consultants in Kansas City, Mo.

The friction of water running inside pipes affects the balancing act, too, reducing system pressure by 3 to 5 psi or more. Friction rises as the square of speed, so water during high demand that flows twice as fast as water during low demand creates four times the friction loss. "Old pipes, especially if they have a lot of sediment or encrustation," O'Malley says, "can cause some real friction problems." —*Mark Fischetti*

SHAPES deceive. Virtually all tanks are cylindrical to equally distribute water weight among support columns. Municipalities may add facades for aesthetics or advertising. Clockwise from top left: Forcalquier, France; New York City; Kuwait; Honolulu, Hawaii.

DANIELS & DANIELS (*illustrations*); CHRIS HELLIER *Corbis* (*castle*); CORBIS (*rooftops*); KEVIN SCHAFER *Corbis* (*stripes*); DOUGLAS PEEBLES *Corbis* (*pineapple*)

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DID YOU KNOW...

HEAVY LOAD: A common tank may hold one million gallons of water, which weighs 8.3 million pounds. Large concrete footings must bear this burden as well as transverse loads from 100-mile-per-hour winds against the tank (the standard storm rating). The earth at a suitable site must therefore be very dense, if not rock. On plains where the ground is largely glacial till, such as in North Dakota, steel pilings to anchor footings may have to be driven 100 feet into the ground.

STERILIZE: Tanks are emptied annually and disinfected with a spray of chlorine and possibly ammonia. Sulfur dioxide may be added to the runoff to neutralize an environmental threat from chlorine. Most towns of any size have more than one tank for ample supply and pressure, which allows for maintenance rotation.

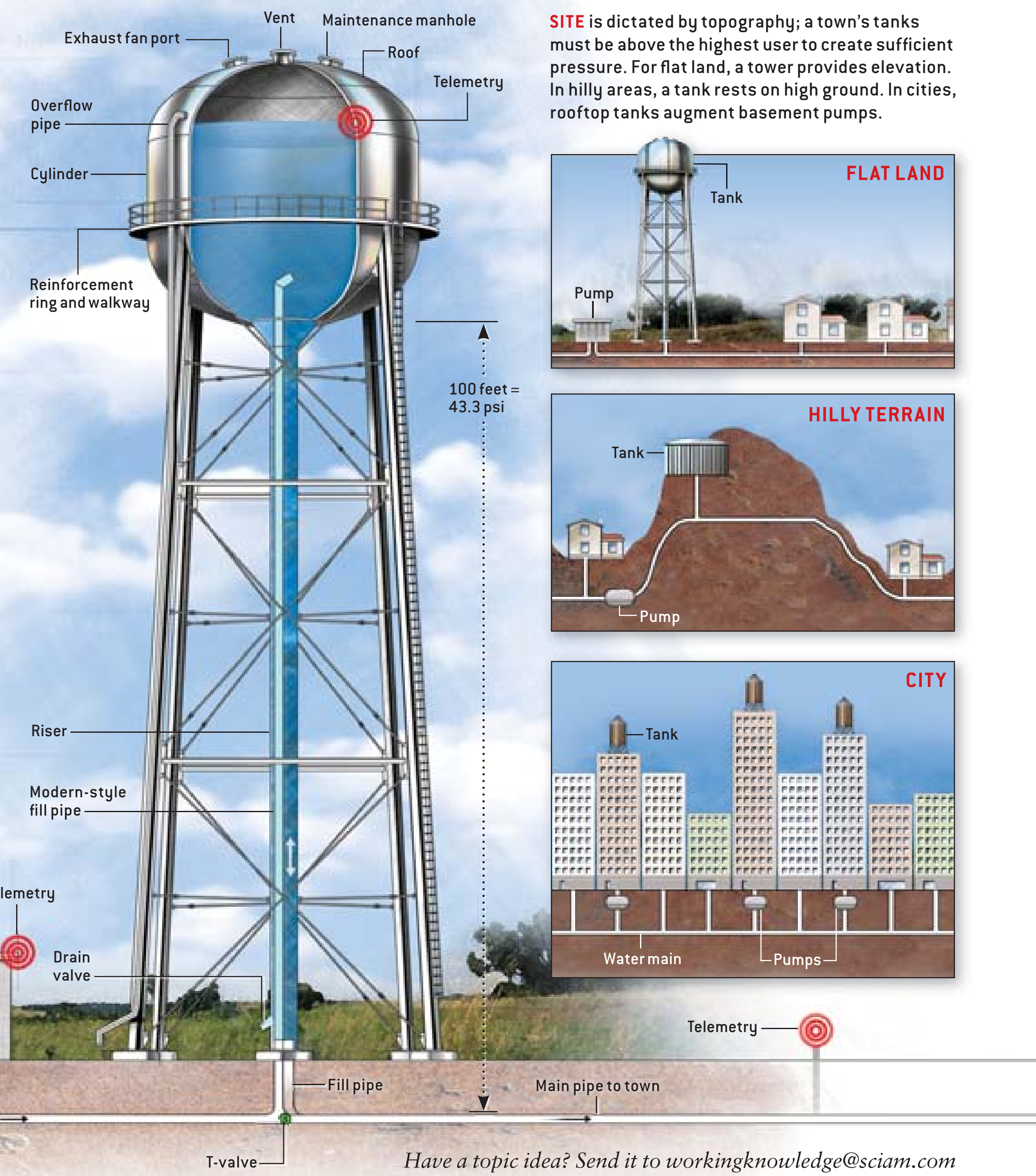
NO PRESSURE: Firefighters who open hydrants in the spring are not relieving excess pressure, as often rumored. They are making sure hydrant valves work and are flushing lines of possible pressure-reducing sediment buildup.

CELL SALES: Many municipalities are leasing tank-top space to telecom providers, because cell phone transceivers provide excellent service when they hover 100 to 150 feet above callers—the typical height of water towers.

TANK is typically a steel cylinder joined to a roof and bottom. A vent allows air to enter and escape as the tank empties or fills, so a vacuum or high pressure does not distort the roof. An exhaust fan expels fumes during regular sterilization and interior painting.

PUMP forces water up a riser, and water exits through the same T-joint to town pipes. New designs include a higher, angled fill pipe to better mix contents, reducing the possibility of stagnant tank water. Telemetry monitors tank water level and pressure in pipes and tells pumps to turn on or off.

SITE is dictated by topography; a town's tanks must be above the highest user to create sufficient pressure. For flat land, a tower provides elevation. In hilly areas, a tank rests on high ground. In cities, rooftop tanks augment basement pumps.



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The Inelegant Universe

TWO NEW BOOKS ARGUE THAT IT IS TIME FOR STRING THEORY TO GIVE WAY **BY GEORGE JOHNSON**

THE TROUBLE WITH PHYSICS: THE RISE OF STRING THEORY, THE FALL OF A SCIENCE, AND WHAT COMES NEXT
by Lee Smolin
Houghton Mifflin, 2006 ($26)

NOT EVEN WRONG: THE FAILURE OF STRING THEORY AND THE SEARCH FOR UNITY IN PHYSICAL LAW
by Peter Woit
Basic Books, 2006 ($26.95)

When you click the link for the Postmodernism Generator (www.elsewhere.org/pomo), a software robot working behind the scenes instantly throws together a lit-crit parody with a title like this: "Realities of Absurdity: The dialectic paradigm of context in the works of Fellini." And a text that runs along these lines: "In a sense, the main theme of the works of Fellini is the futility, and hence the stasis, of precapitalist sexuality. An abundance of deconceptualisms concerning a self-falsifying reality may be revealed."

Reload the page, and you get "The Dialectic of Sexual Identity: Objectivism and Baudrillardist hyperreality" and then "The Meaninglessness of Expression: Capitalist feminism in the works of Pynchon."

With a tweak to the algorithms and a different database, the Web site could probably be made to spit out what appear to be abstracts about superstring theory: "Frobenius transformation, mirror map and instanton numbers" or "Fractional two-branes, toric orbifolds and the quantum McKay correspondence."

Those are actually titles of papers recently posted to the arXiv.org repository of preprints in theoretical physics, and they may well be of scientific worth—if, that is, superstring theory really is a science. Two new books suggest otherwise: that the frenzy of research into strings and branes and curled-up dimensions is a case of surface without depth, a solipsistic shuffling of symbols as relevant to understanding the universe as randomly generated dadaist prose.

In this grim assessment, string theory—an attempt to weave together general relativity and quantum mechanics—is not just untested but untestable, incapable of ever making predictions that can be experimentally checked. With no means to verify its truth, superstring theory, in the words of Burton Richter, director emeritus of the Stanford Linear Accelerator Center, may turn out to be "a kind of metaphysical wonderland." Yet it is being pursued as vigorously as ever, its critics complain, treated as the only game in town.

"String theory now has such a dominant position in the academy that it is practically career suicide for young theoretical physicists not to join the field," writes Lee Smolin, a physicist at the Perimeter Institute for Theoretical Physics, in *The Trouble with Physics: The Rise of String Theory, the Fall of a Science, and What Comes Next*. "Some young string theorists have told me that they feel constrained to work on string theory whether or not they believe in it, because it is perceived as the ticket to a professorship at a university."

The counterargument, of course, is that string theory is dominant because the majority of theorists sense that it is the most promising approach—that the vision of oscillating strings singing the cosmic harmonies is so beautiful that it has to be true. But even that virtue is being called into question. "Once one starts learning the details of ten-dimensional superstring theory, anomaly cancellation, Calabi-Yau spaces, etc., one realizes that a vibrating string and its musical notes have only a poetic relationship to the real thing at issue," writes Peter Woit, a lecturer in mathematics at Columbia University, in *Not*

PATIENCE with string theory may be fraying.

NICK KOUDIS *Getty Images*

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Even Wrong: The Failure of String Theory and the Search for Unity in Physical Law. The contortions required to hide away the seemingly nonexistent extra dimensions have resulted in structures Woit finds "exceedingly complex" and "exceedingly ugly."

Many physicists will take exception to such harsh judgments (three sympathetic treatments of superstrings were reviewed here in April). But neither of these books can be dismissed as a diatribe. Both Smolin and Woit acknowledge that some important mathematics has come from contemplating superstrings. But with no proper theory in sight, they assert, it is time to move on. "The one thing everyone who cares about fundamental physics seems to agree on is that new ideas are needed," Smolin writes. "We are missing something big."

The story of how a backwater of theoretical physics became not just the rage but the establishment has all the booms and busts of an Old West mining town. Unable to fit the four forces of nature under the same roof, a few theorists in the 1970s began adding extra rooms—the seven dimensions of additional closet space that unification seemed to demand. With some mathematical sleight of hand, these unseen dimensions could be curled up ("compactified") and hidden inside the cracks of the theory, but there were an infinite number of ways to do this. One of the arrangements might describe this universe, but which?

The despair turned to excitement when the possibilities were reduced to five and to exhilaration when, in the mid-1990s, the five were funneled into something called M Theory, which promised to be the one true way. There were even hopes of experimental verification. A piece I wrote around that time carried this now embarrassing headline: "Physicists Finally Find a Way to Test Superstring Theory."

That was six years ago, and to hear

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Smolin and Woit tell it, the field is back to square one: recent research suggests that there are, in fact, some 10^{500} perfectly good M theories, each describing a different physics. The theory of everything, as Smolin puts it, has become a theory of anything.

Faced with this free-for-all, some string theorists have concluded that there is no unique theory, that the universe is not elegant but accidental. If so, trying to explain the value of the cosmological constant would make as much sense as seeking a deep mathematical reason for why stop signs are octagonal or why there are 33 human vertebrae.

Most theorists reject this postmodern fatalism, hoping for the breakthrough that points the way to the mountaintop. Gathering in Beijing this summer for the Strings 2006 conference, they packed the Great Hall of the People to hear Stephen Hawking declare: "We are close to answering an age-old question. Why are we here? Where did we come from?"

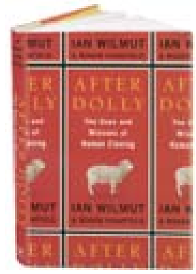
The answer, they hope, is not "Just because." SA

George Johnson's books include Fire in the Mind: Science, Faith, and the Search for Order *and* Strange Beauty: Murray Gell-Mann and the Revolution in 20th-Century Physics. *He resides on the Web at talaya.net*

THE EDITORS **RECOMMEND**

AFTER DOLLY: THE USES AND MISUSES OF HUMAN CLONING

by Ian Wilmut and Roger Highfield. W. W. Norton, 2006 ($24.95)

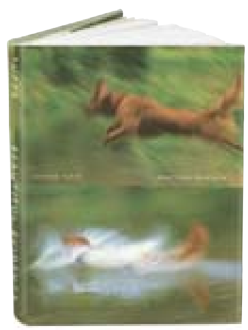


"Fictional fascination with cloning has rarely focused on scientific fact but usually on issues of identity and how the sanctity of life will be challenged when 'ditto machines' of one kind or another create 'cookie cutter humans.' This obsession has led to endless confusion about what is possible and what is not." So writes Wilmut, leader of the team that 10 years ago cloned Dolly, the first animal created from an adult cell. He and Highfield, science editor of the *Daily Telegraph* in England, set out to separate fact from fiction. They succeed beautifully and go on to provide a forceful moral argument for cloning and its power to fight, and even eradicate, some of the most terrible diseases in existence. At the same time, this pioneer of cloning remains staunch in his opposition to using the procedure for human reproduction.

The book, despite its weighty concerns, avoids a moralizing tone and is exceedingly pleasant to read. To give a taste of the style: in explaining the arthritis that developed in Dolly's knee—unrelated, so far as they can tell, to cloning—the authors conclude that perhaps the condition "was inevitable for a corpulent sheep who had been indulged all her life and liked to stand up and beg on her rear legs."

BEAUTIFUL EVIDENCE

by Edward Tufte. Graphics Press, 2006 ($52)



"Science and art," according to Tufte, "have in common *intense seeing,* the wide-eyed observing that generates empirical information." This book is about how that seeing turns into showing. Tufte, professor emeritus at Yale University and author of three previous widely praised books on visual evidence, displays outstanding examples of the genre. One of the most arresting is Galileo's series of hand-drawn images of sunspots. A colleague of Galileo, the author tells us, said that the astronomer's drawings "delight both by the wonder of the spectacle and the accuracy of expression." That, Tufte says, is beautiful evidence.

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Requiem for a Heavyweight

A SLOW AND STEADY—AND EXCEPTIONALLY LENGTHY—LIFE **BY STEVE MIRSKY**

Four score and seven years and four score and nine more years ago, a tortoise hatched in the Galápagos. She spent the past half a century known as Harriet. For more than a century before that, she was called Harry. Before that she almost was called dinner, but fate had other plans. Her heart, which began beating when Abraham Lincoln was barely out of his teens, finally stopped on June 23.

Her fame came from her longevity and from her celebrity friends. She spent her last years at the Australia Zoo in Queensland, run by Terri and Steve "the Crocodile Hunter" Irwin. And she was most likely rescued from the soup tureen that she strongly resembled by Charles Darwin. Yes, that Charles Darwin, born the same day as Lincoln.

"I find her walk through time to be extraordinary," says Scott Thomson, a paleontologist and taxonomist at the University of Canberra in Australia, whose analysis of Harriet's DNA helped to show that her life began in 1830, give or take a couple years. Most of Harriet's history was hidden when Thomson started snooping around in the early 1990s as part of an effort aimed at determining the subspecies of all Galápagos tortoises in Australia. When that project started, Thomson knew that Harriet had come to the Australia Zoo (then known as the Queensland Reptile Park) in 1987. As Thomson, Irwin and Irwin wrote in a 1998 article in the journal *Reptilia,* in 1952 Harriet began living at a place called Fleay's Fauna Sanctuary. There she was finally recognized to have been a female all along. The mix-up is understandable, because determining the sex of a giant tortoise is problematic. For one thing, turning over a 330-pound, shelled reptile is no small feat. (Small feet are no giveaway either.) Internal genitalia make the exercise largely pointless anyway.

Pre-Fleay, she was at the Brisbane Botanical Gardens, living as Harry, named after the curator, one Harry Oakmann. (Some of the gardens' trees may also have been named for him.)

And records showed that Harry/Harriet was there at least as far back as 1870. A break in the case came in 1994, when an Australian newspaper ran a story about another giant tortoise, called Lonesome George because of his status as the last member of his subspecies. The article prompted a newspaper letter from a retired historian who remembered seeing tortoises, including Harry/Harriet, in Brisbane back in the 1920s—and being told that they had been brought by a Captain Wickham from England.

Wickham was first lieutenant to Captain FitzRoy on the *Beagle,* the ship that carried the young naturalist Charles Darwin from 1831 to 1836. And Darwin was the most likely person to have collected Harriet.

Some reports pour cold water on the Darwin connection, because Thomson's DNA analysis showed that Harriet was a member of a subspecies native to Santa Cruz island, which Darwin never visited. But Darwin did collect tortoises on Santa Maria island—even though the Marian subspecies had been driven to extinction by hungry inmates of the local prison, unfamiliar with the concept of sustainable development. The prison thus restocked its cupboards with tortoises captured on other Galápagos islands. Strong circumstantial evidence therefore puts the juvenile Harriet on Santa Cruz, where she gets incarcerated by cons, carried to Santa Maria and plucked from the pot by Darwin.

After that near-broth experience, the next 170 years were a cakewalk. But all good things, even those long postponed, must finally end. "It's very sad that she died," Thomson says. "I knew Harriet for over 20 years, and she came to mean a lot to me. She loved people more than any other tortoise I have ever met." And the *Times* of London, not ordinarily given to eulogizing tortoises, paid this tribute: "Harriet created less trouble in the world than any other living creature, four-legged or biped." She certainly caused less trouble for some people than that biped Darwin. SA

ILLUSTRATION BY MATT COLLINS; PHOTOGRAPH BY FRANK VERONSKY

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How do batteries store and discharge electricity?

—D. Dodds, Detroit

Kenneth Buckle, a visiting scientist at the Center for Integrated Manufacturing Studies at the Rochester Institute of Technology, provides this answer:

When connected to a load like a lightbulb, a typical battery undergoes chemical reactions that release electrons, which travel through the bulb and are then reabsorbed by the battery. (Devices that store mechanical energy also exist, but the most common batteries, such as those used in flashlights and remotes, hold energy in chemical form.) Inside is at least one galvanic cell, which produces between zero and several volts, depending on its chemistry. In a car battery, six cells, each contributing two volts, are connected in series to make a 12-volt battery.

All electrochemical cells consist of two electrodes separated by some distance. The space between the electrodes is filled with an electrolyte, a liquid or solid containing charged particles, or ions. One electrode—the anode—emits negatively charged electrons. The other—the cathode—receives them. Chemical differences between the two electrodes create an energy difference, or potential, that moves electrons from the anode to the cathode via the electrolyte. For example, the lead-acid cell uses a lead oxide cathode, a lead anode and a sulfuric acid (liquid) electrolyte.

In this case, sulfuric acid creates an environment that stretches the chemical bonds of the lead and lead oxide, so oxidation and reduction reactions occur simultaneously. In the reduction reaction the acid strips the oxygen from the lead-oxide cathode and replaces it with sulfate. The oxide ion then combines with hydrogen (from the acid) and forms water. In oxidation the sulfuric acid coaxes two electrons away from the lead and then latches on to form lead sulfate. If the battery is attached to a load, the electrons that the sulfate replaces travel out of the cell and into the load, creating an electric current.

A galvanic cell can continue to discharge electrons until either or both electrodes run out of reagents, the compounds that drive the oxidation/reduction reactions. In a nonrechargeable battery the chemical reaction that created the energy is not easily reversible, and when the reagents run out the cell is unusable. In a rechargeable battery, such as the lead-acid cell, the reaction is reversible, meaning that an external source of direct electric current can force the electrons to flow from the cathode to the anode until the cell is recharged.

Does damp weather make arthritis pain worse?

—C. Levy, Falls Church, Va.

Donald A. Redelmeier, a professor of medicine at the University of Toronto, explains:

Despite the commonly held notion that dampness contributes to joint aches, decades of medical research show no objective relation between arthritis severity and weather.

Dampness, decreases in barometric pressure and high humidity are characteristics that some people believe contribute to flares in arthritis pain, but similar environmental changes experienced during other situations do not seem to affect sufferers one way or the other. For instance, arthritis patients do not experience dramatic increases in symptoms when bathing or swimming. Patients easily tolerate greater swings in pressure during a plane ride than would occur during a storm.

Still, no past study investigating the link between weather and arthritic pain is flawless; research has neither totally ruled out nor established a connection. Evidence of a causal link requires dispassionate observation wherein neither clinicians nor patients know what exposure is active. Clinicians and patients would have to ignore weather—a difficult task.

Studies suggest people see patterns even where none exist. By chance, some rainy days will be followed by pain, entrenching the belief in a connection. Ultimately, such beliefs reveal more about the workings of the mind than those of the body. SA

For a complete text of these and other answers from scientists in diverse fields, visit www.sciam.com/askexpert

MATT COLLINS

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