

The Rise of *Renewable* Energy

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.

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



KENN BROWN

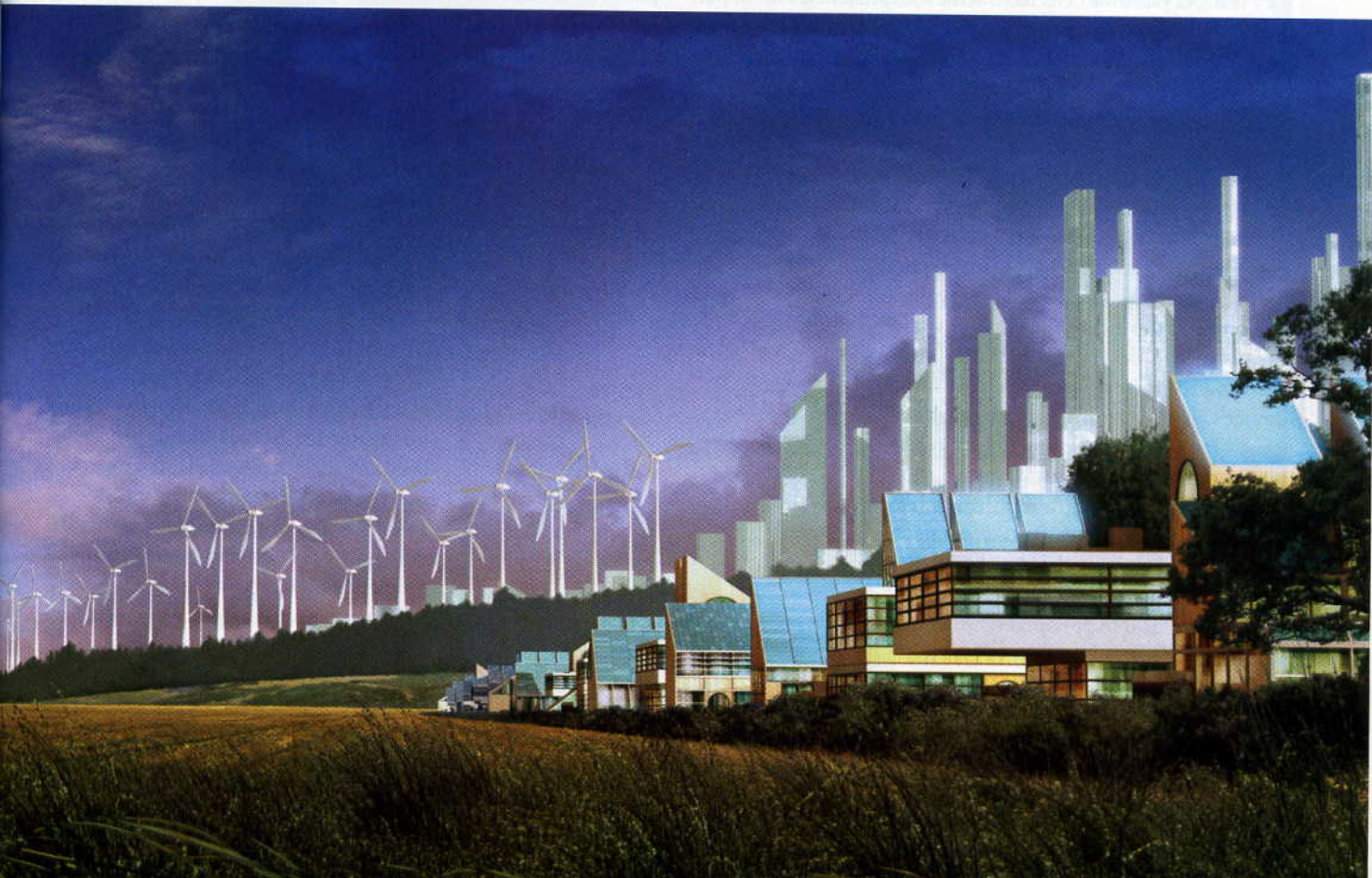
No plan to substantially reduce greenhouse gas emissions can succeed through increases in energy efficiency alone. Because economic growth continues to boost the demand for energy—more coal for powering new factories, more oil for fueling new cars, more natural gas for heating new homes—carbon emissions 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.



opportunities 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.

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

**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

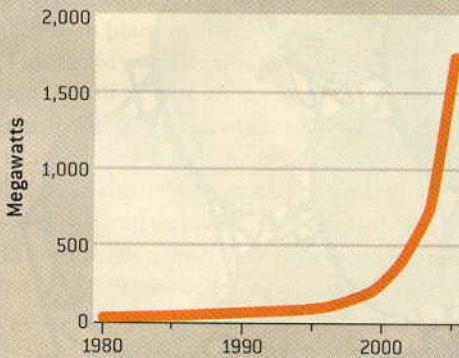
GROWING FAST, BUT STILL A SLIVER

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.

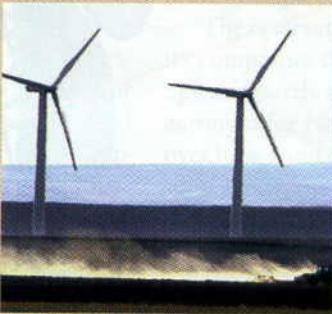
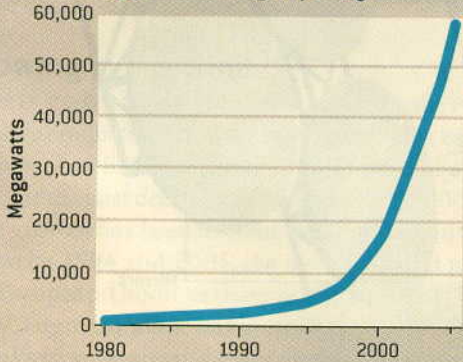
THE RENEWABLE BOOM

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

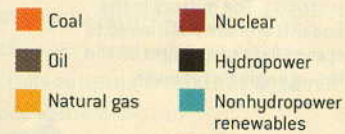


Ethanol Production



COMPETING ENERGY SOURCES

Fraction of global electricity generation



Breakdown of nonhydropower renewables



THE CHALLENGE AHEAD

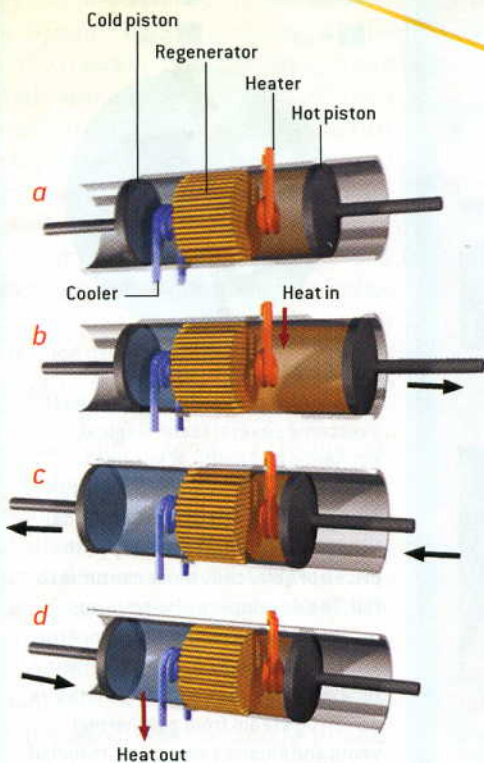
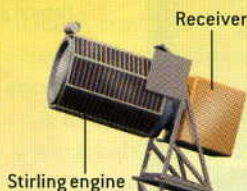
Suppliers of renewable energy must overcome several technological, economic and political hurdles to rival the market share of the fossil-fuel providers. To compete with coal-fired power plants, for example, the prices of solar cells must continue to fall. The developers of wind farms must tackle environmental 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.

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.

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.

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

**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

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.

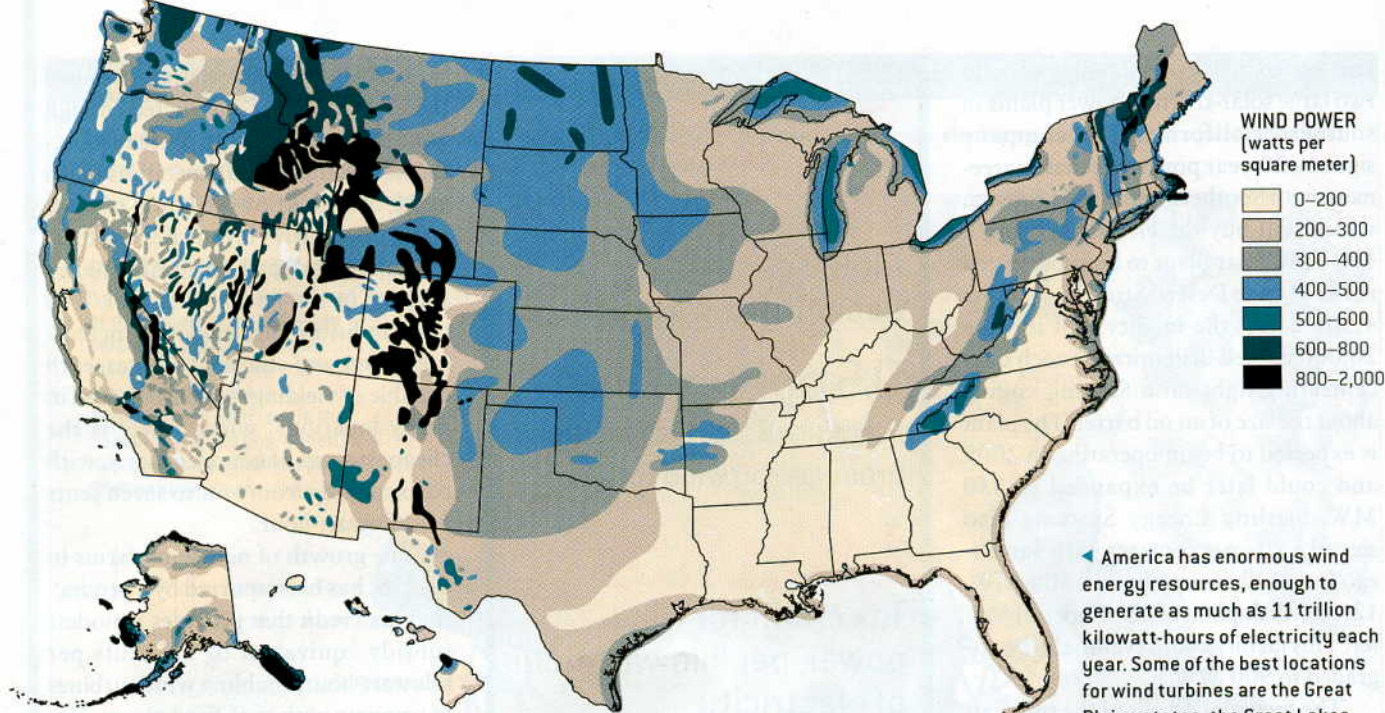
The reservations about wind power come partly from utility companies that are reluctant to embrace the new technology and partly from so-called NIMBY-ism. ("NIMBY" is an acronym for Not in My Backyard.) Although local concerns over how wind turbines will affect landscape views may have some merit, they 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

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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

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.

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].

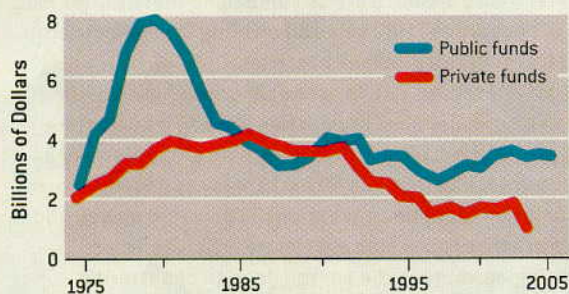
To put these declines in perspective, consider that in the early 1980s energy companies were investing more in R&D than were drug companies, whereas today investment by energy firms is an order of magnitude lower. Total private R&D funding for the entire energy sector is less than that of a single

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.

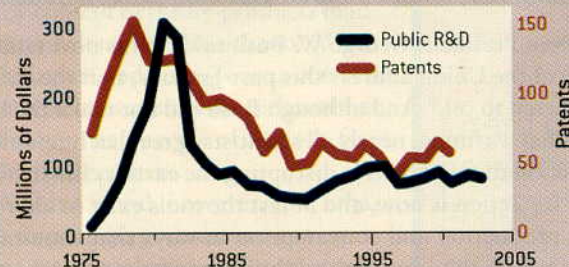
R&D IS KEY

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.

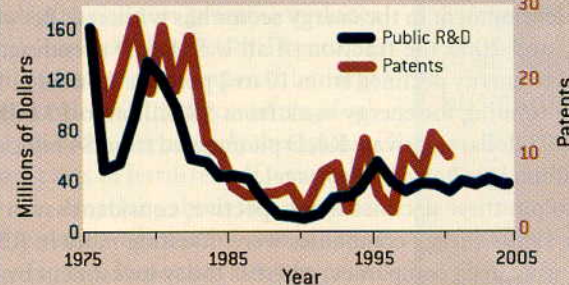
U.S. R&D SPENDING IN THE ENERGY SECTOR



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-

THE LEAST BAD FOSSIL FUEL

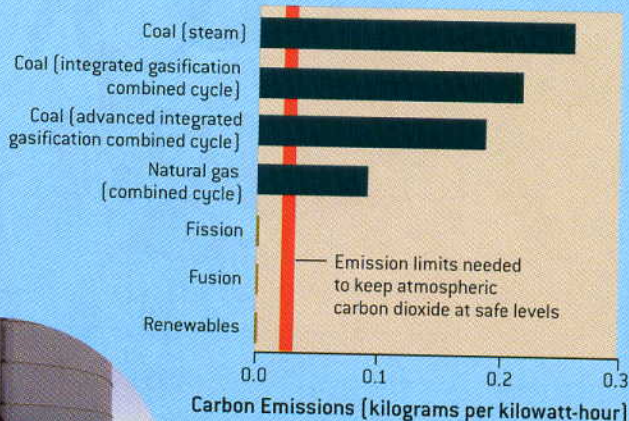
Although renewable energy sources offer the best way to radically cut greenhouse gas emissions, generating electricity from natural gas instead of coal can significantly reduce the amount of carbon added to the atmosphere. Conventional coal-fired power plants emit 0.25 kilogram of carbon for every kilowatt-hour generated. (More advanced coal-fired plants produce about 20 percent less carbon.) But natural gas (CH₄) 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



HOW POWER PLANT EMISSIONS STACK UP



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.

igned 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.

MORE TO EXPLORE

Reversing the Incredible Shrinking Energy R&D Budget.
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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.

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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>