ENERGY SOLUTIONS FOR A SUSTAINABLE WORLD

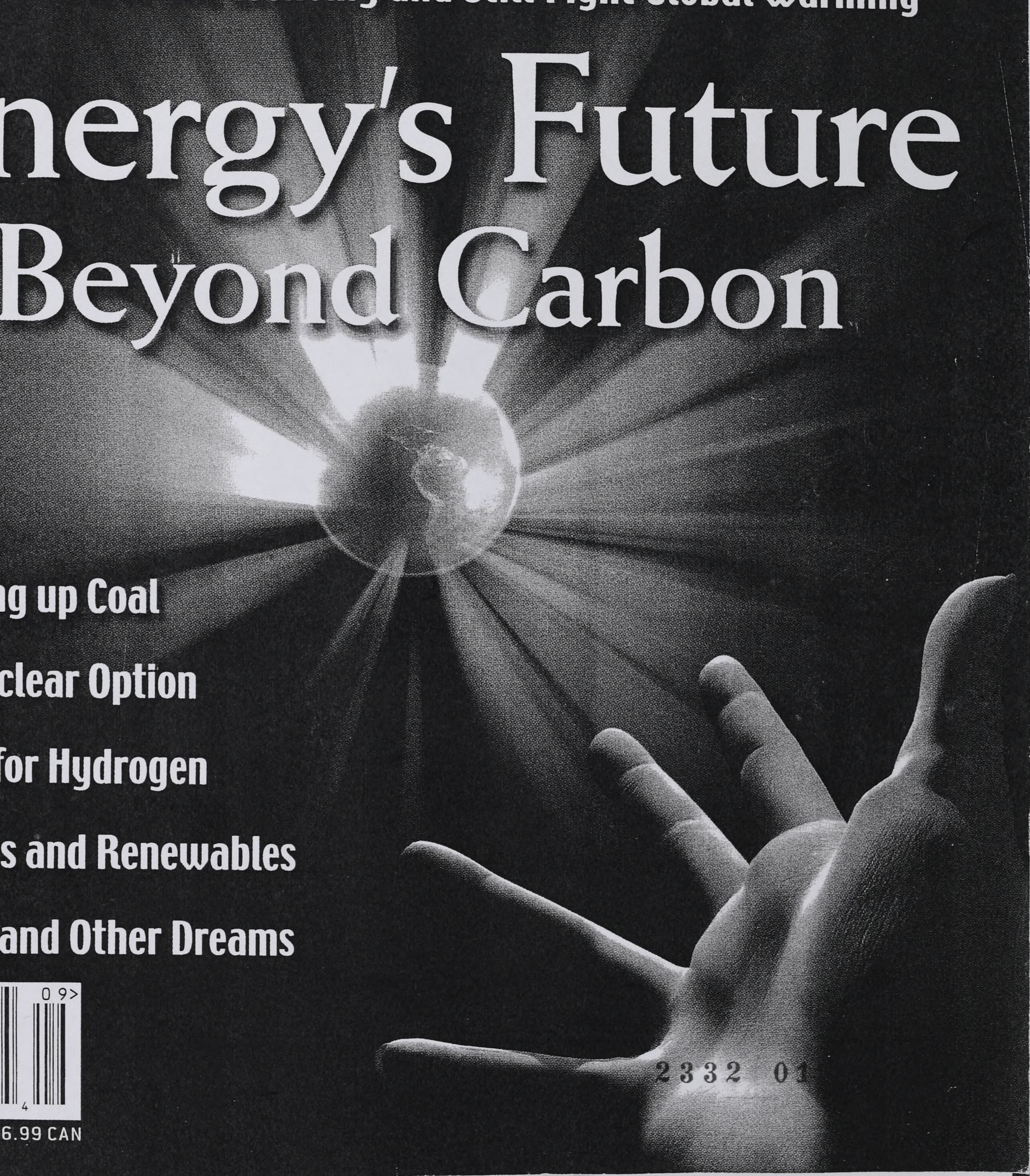
SCIENTIFIC AMERICAN

SPECIAL ISSUE

SEPTEMBER 2006
WWW.SCIAM.COM

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

09>
0 70992 38529 4
$4.99 U.S. $6.99 CAN

2332 01

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.

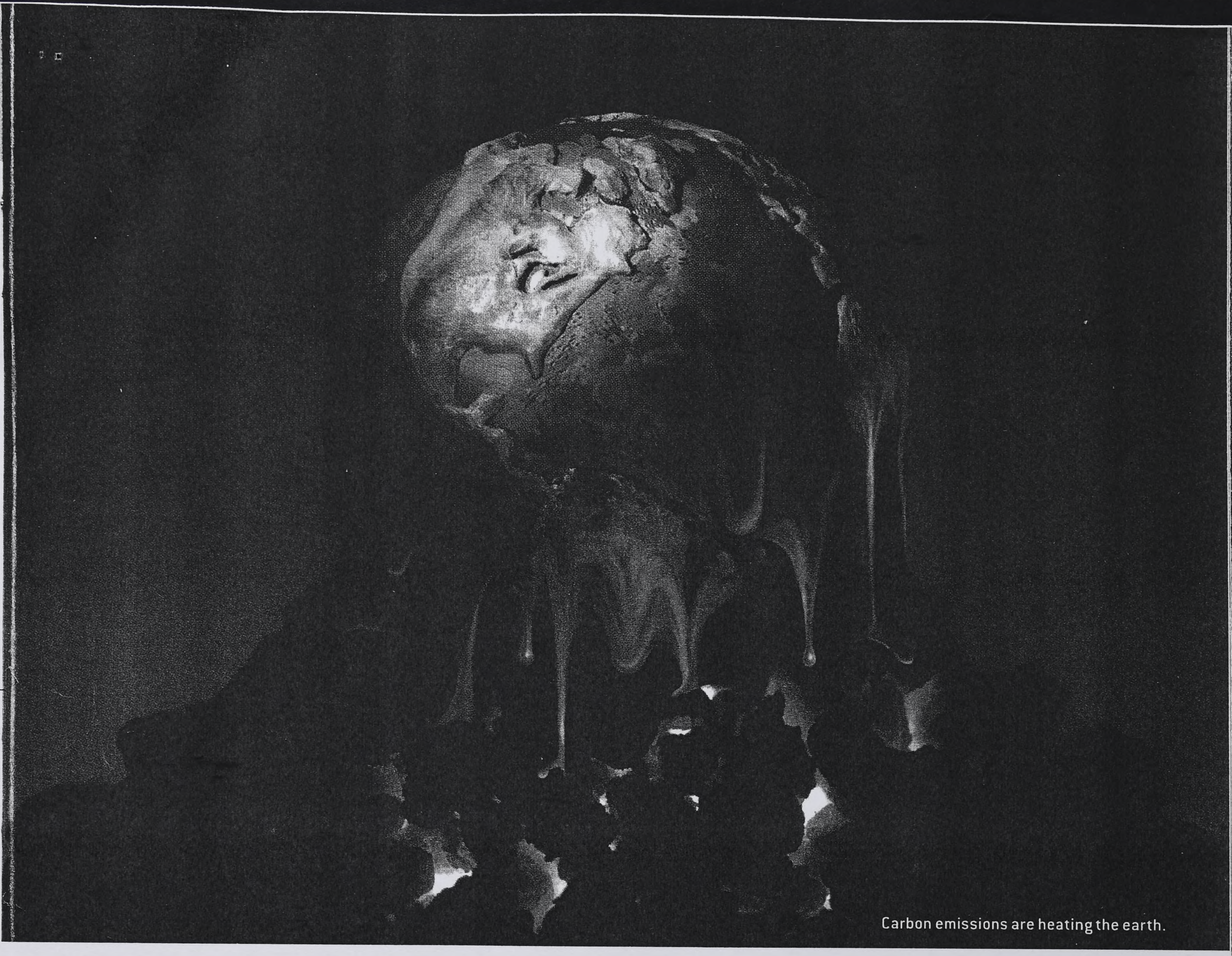
Explorers attempted and mostly failed over the centuries to establish a pathway from the Atlantic to the Pacific through the icebound North, a quest often punctuated by starvation and scurvy. Yet within just 40 years, and maybe many fewer, an ascending thermometer will likely mean that the maritime dream 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-



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.

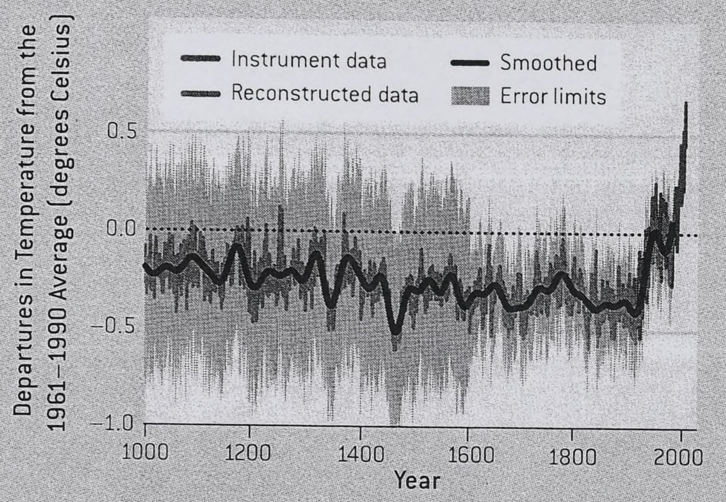
Translation of scientific consensus on climate change into a consensus on what should be done about it carries the debate into the type of political minefield that has often undercut attempts at international governance since the League of Nations. The U.S. holds less than 5 percent of the world's population 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

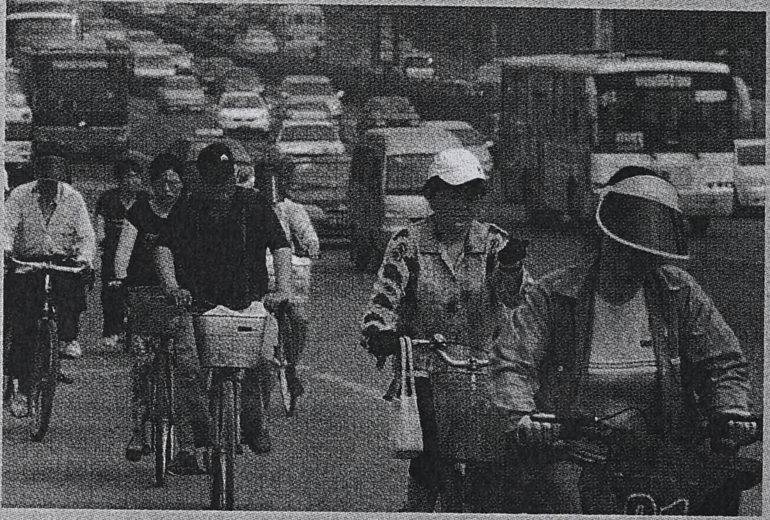
THE HEAT IS ON

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.



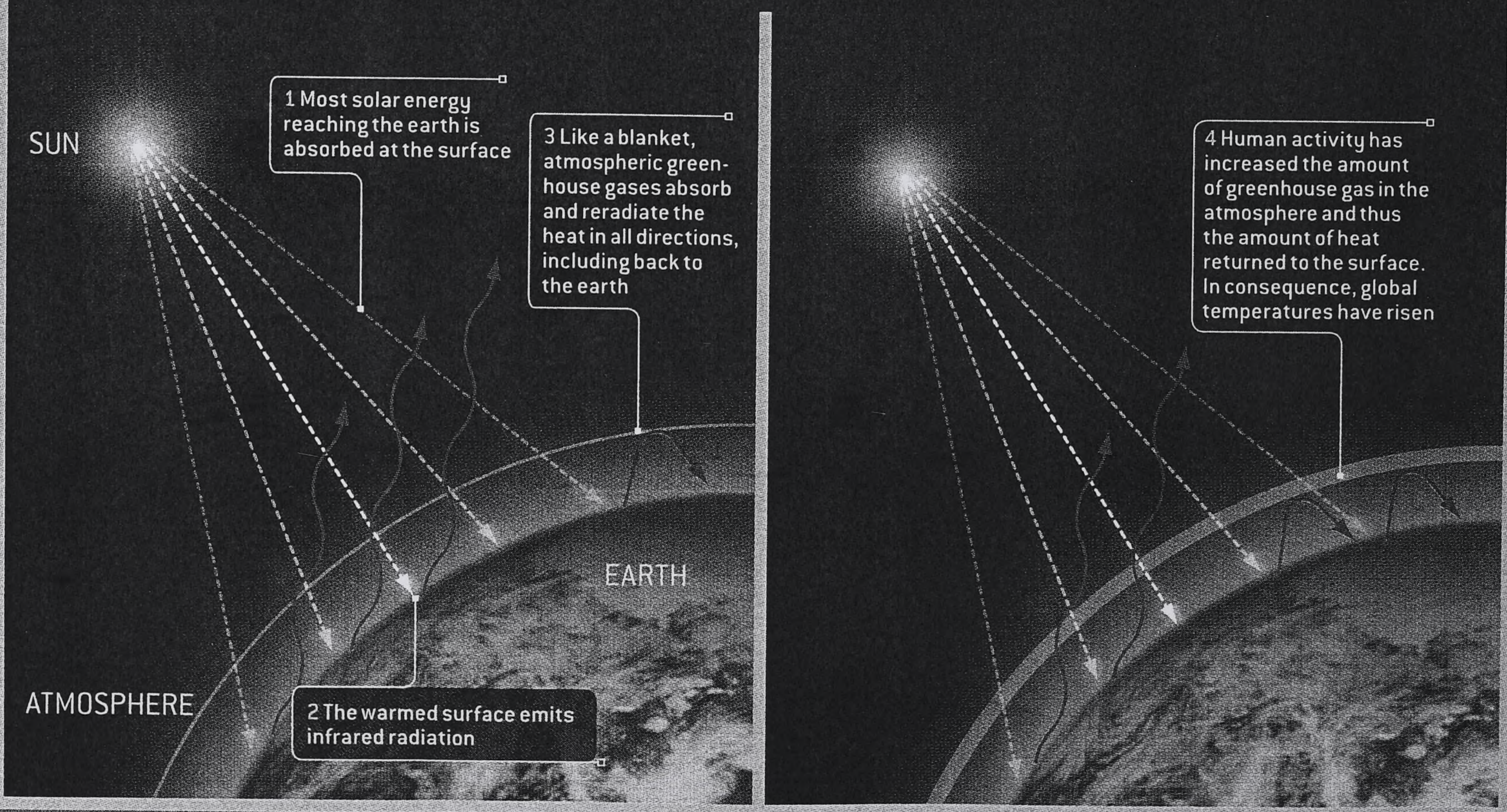
This "hockey stick graph," from one of many studies showing a recent sharp increase in average temperatures, received criticism from warming skeptics, who questioned the underlying data. A report released in June by the National Research Council lends new credence to the sticklike trend line that traces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

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

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.

FREDERIC J. BROWN AFP/Getty Images (China); COLT READING-IKKANDA (illustrations)

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

▶ 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

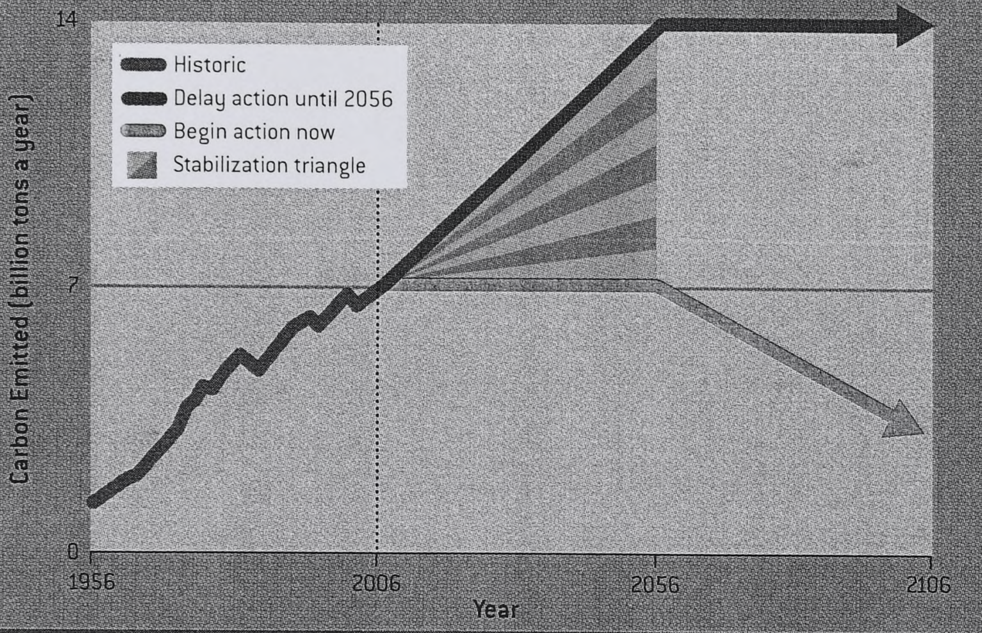
KENN BROWN

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.

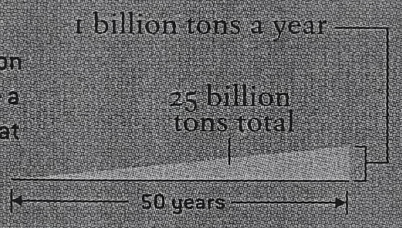
ANNUAL EMISSIONS

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.



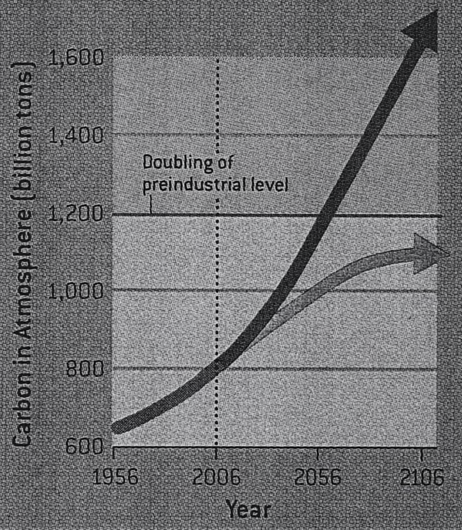
THE WEDGE CONCEPT

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

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.

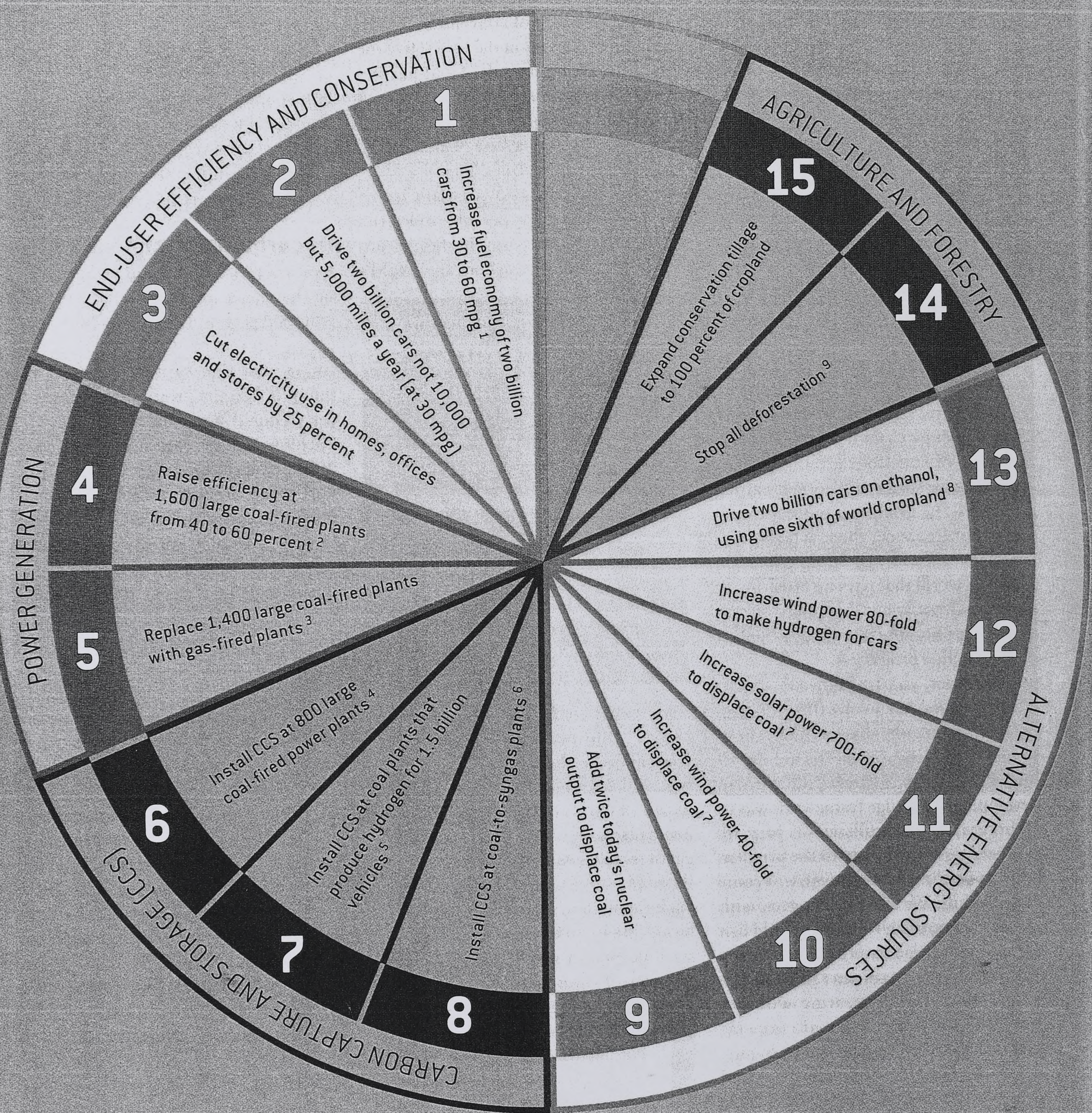
The large natural gas power plants operating in 2056 could capture and store their CO_2, too, perhaps accounting for yet another wedge. Renewable and nuclear energy can contribute as well. Renewable power can be produced from sunlight directly, either to energize photovoltaic cells or, using focusing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

THE AUTHORS

ROBERT H. SOCOLOW and STEPHEN W. PACALA lead the Carbon Mitigation Initiative at Princeton University, where Socolow is a mechanical engineering professor and Pacala an ecology professor. The initiative is funded by BP and Ford. Socolow specializes in energy-efficient technology, global carbon management and carbon sequestration. He was co-editor (with John Harte) of *Patient Earth*, published in 1971 as one of the first college-level presentations of environmental studies. He is the recipient of the 2003 Leo Szilard Lectureship Award from the American Physical Society. Pacala investigates the interaction of the biosphere, atmosphere and hydrosphere on global scales, with an emphasis on the carbon cycle. He is director of the Princeton Environmental Institute.

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

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. 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.

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.

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.

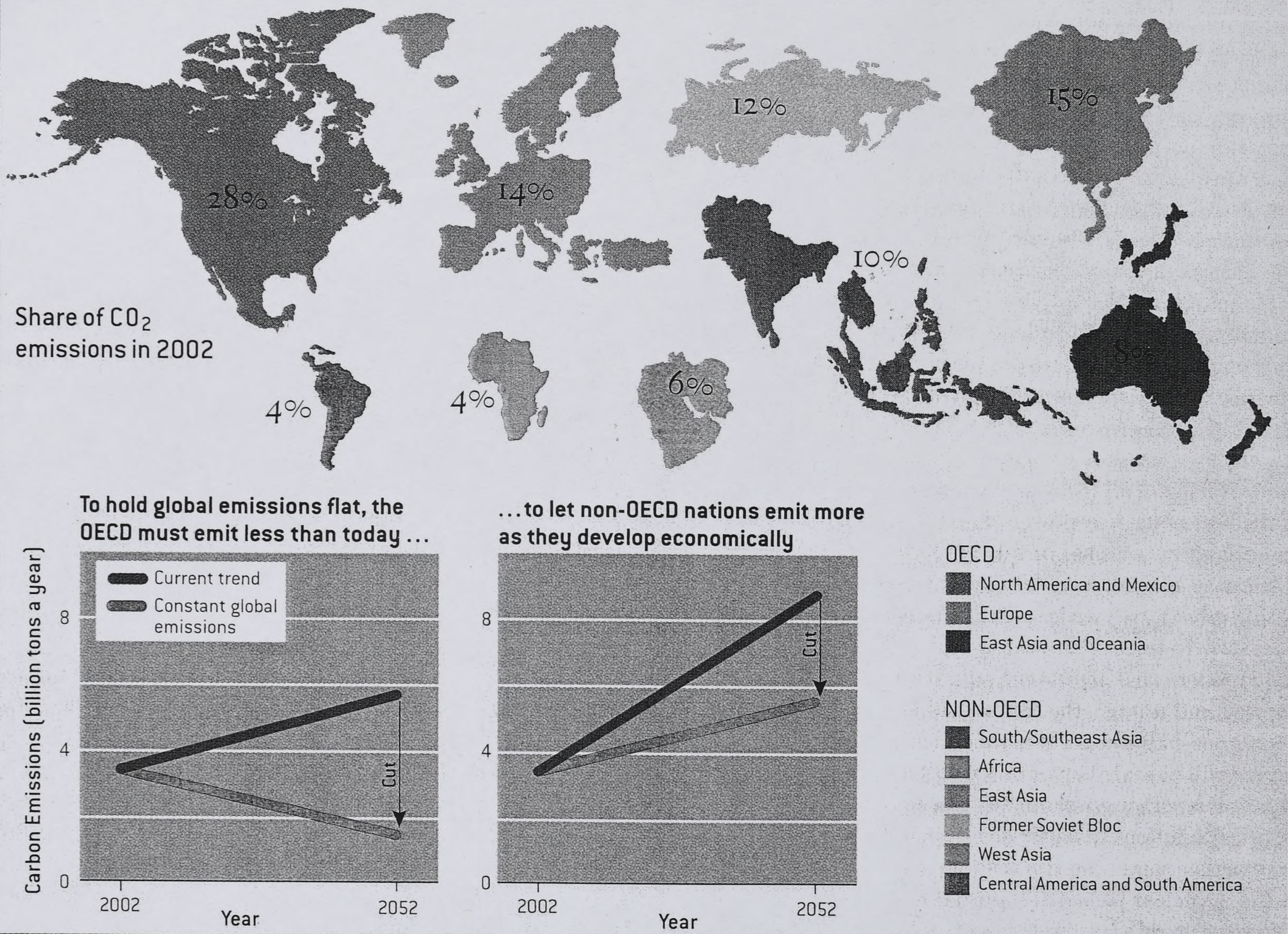
Action Plan

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

JANET CHAO

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.

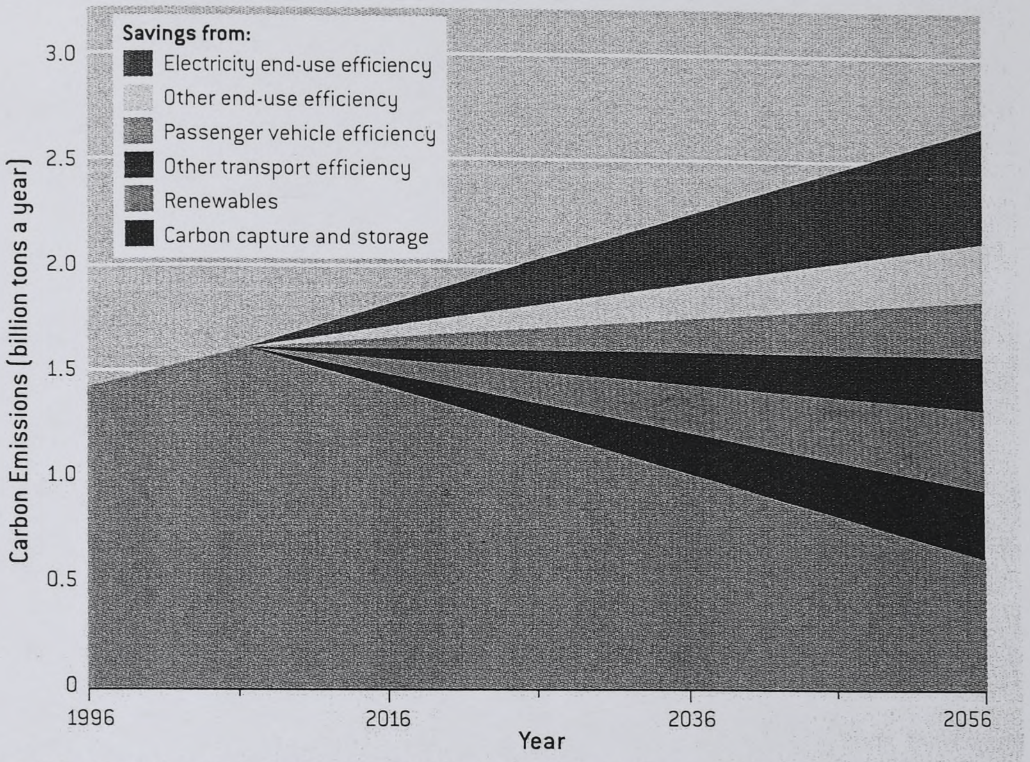
How much less? It is easy to bracket the answer. Currently the industrial nations—the members of the Organization for Economic Cooperation and Development (OECD)—account for almost exactly half the planet's CO_2 emissions, and the developing countries plus the nations formerly part of the Soviet Union 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 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**

IN *TRENDS: A COMPENDIUM OF DATA ON GLOBAL CHANGE*. CARBON DIOXIDE INFORMATION ANALYSIS CENTER, OAK RIDGE NATIONAL LABORATORY, 2006

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

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.

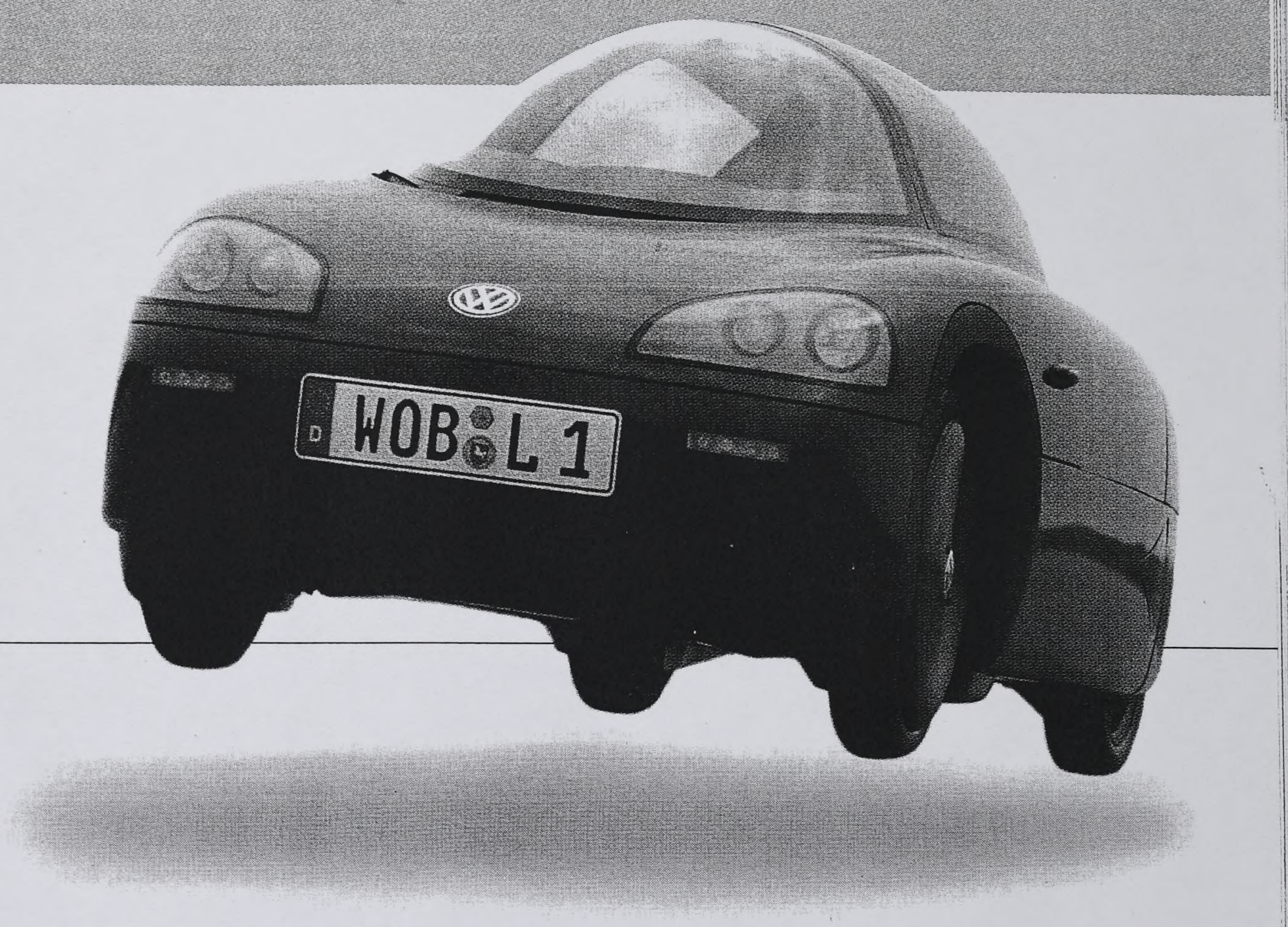
In examining these alternatives, we have to keep in mind several aspects of the existing transportation system. First, it is well suited to its primary context, the developed world. Over decades, it has had time to evolve so that it balances economic costs with users' needs and wants. Second, this vast 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.

ture



▲ 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

THE AUTHOR

JOHN B. HEYWOOD is Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Lab at the Massachusetts Institute of Technology. He was educated at the University of Cambridge and at M.I.T., where he joined the faculty in 1968. He is author of the widely used textbook *Internal Combustion Engine Fundamentals* (McGraw-Hill, 1988) and is a member of the National Academy of Engineering and the American Academy of Arts and Sciences.

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.

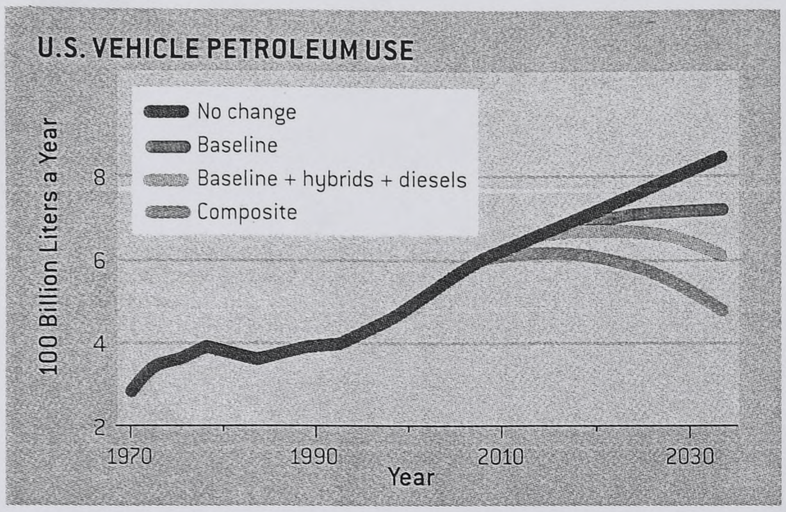
What about new propulsion system technology? Likely innovations would include significantly improved gasoline engines (using a turbocharger with direct fuel injection, for ex-

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*



▲ 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 onboard 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

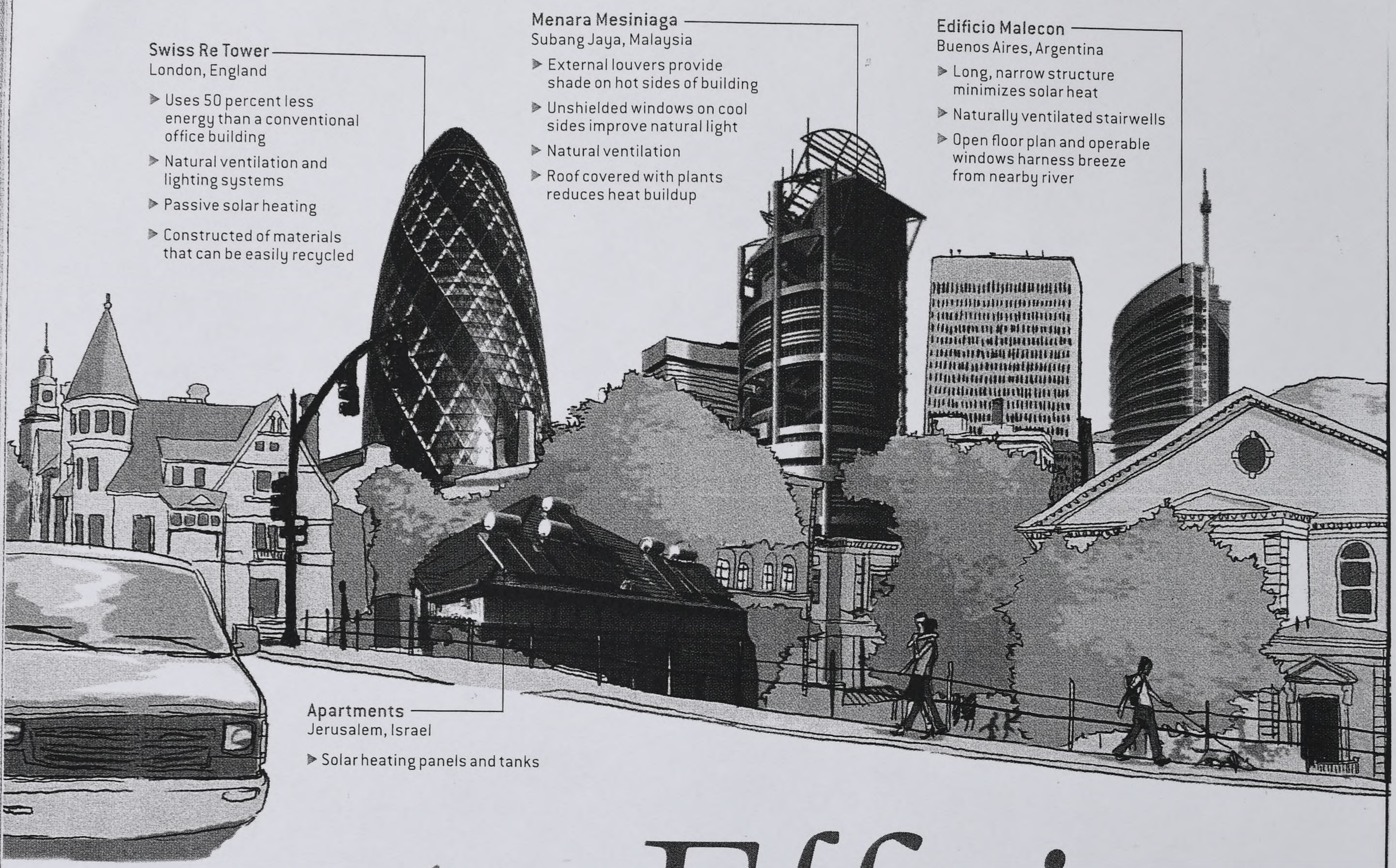
Reducing Gasoline Consumption: Three Policy Options. Congressional Budget Office, November 2002. Available at www.cbo.gov/ftpdocs/39xx/doc3991/11-21-GasolineStudy.pdf

Reducing Greenhouse Gas Emissions from U.S. Transportation. David L. Greene and Andreas Schafer. Pew Center on Global Climate Change, May 2003. Available at www.pewclimate.org/docUploads/ustransp.pdf

Mobility 2030: Meeting the Challenges to Sustainability. World Business Council for Sustainable Development, 2004. Available at www.wbcsd.org/web/publications/mobility/mobility-full.pdf

DOE FreedomCAR and Vehicle Technologies Program's Fact of the Week: www1.eere.energy.gov/vehiclesandfuels/facts/2006_index.html

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



An *Efficient*

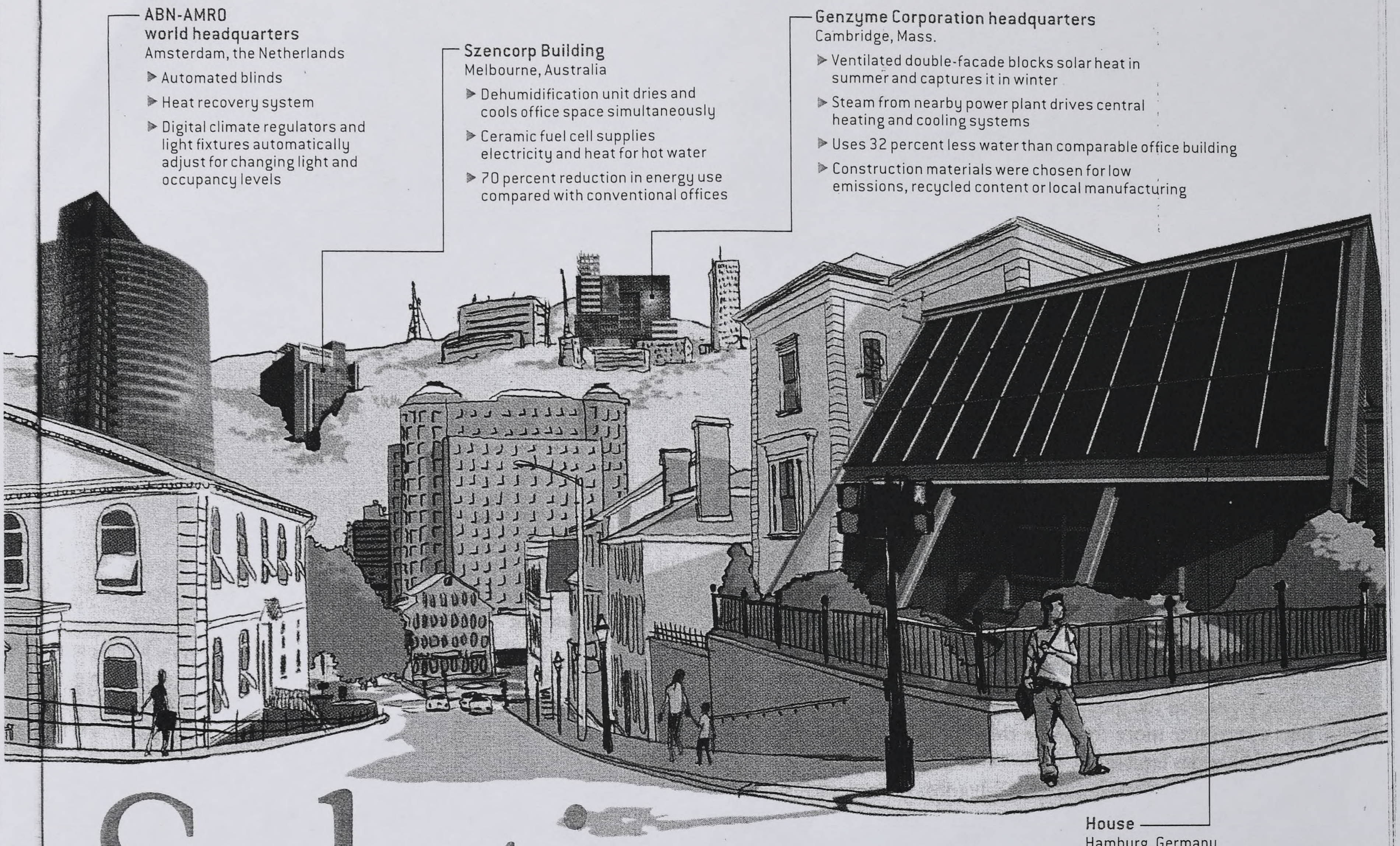
OVERVIEW

- 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.



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

THE AUTHOR

EBERHARD K. JOCHEM is professor of economics and energy economics at the Swiss Federal Institute of Technology (ETH) in Zurich and director of the Center for Energy Policy and Economics there. Educated as a chemical engineer and economist at the technical universities of Aachen and Munich, he was a postdoctoral fellow at the Harvard School of Public Health in 1971 and 1972 before beginning his research in energy and material efficiency at the Fraunhofer Institute for Systems and Innovation Research. He is a member of the editorial board of several scientific journals and of the *Encyclopedia of Energy* and a member of the Swiss Academy of Engineering Sciences.

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

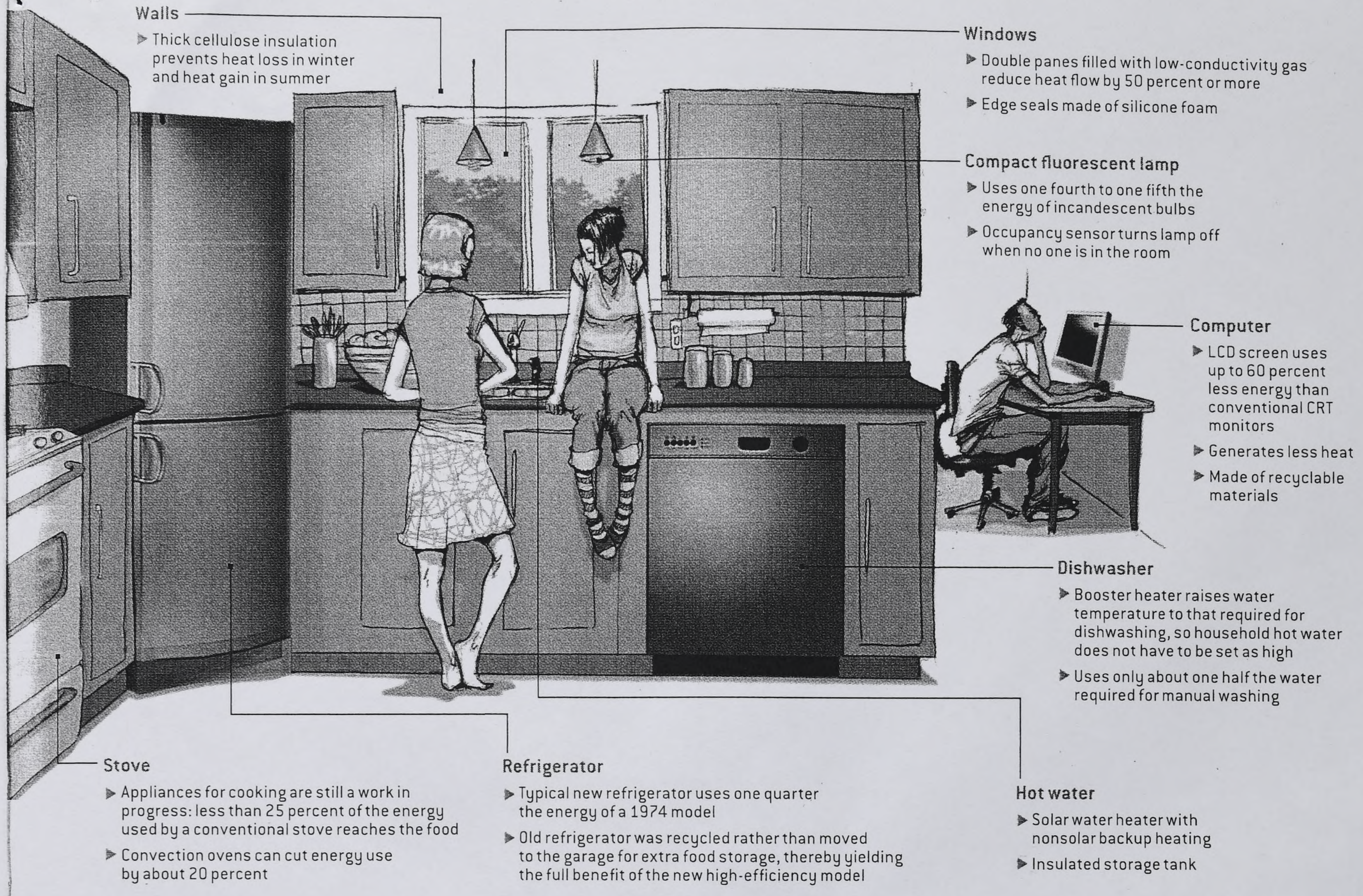
Despite these gains, the biggest steps remain to be taken. Many buildings were designed with the intention of minimizing construction costs rather than life-cycle cost, including energy use, or simply in ignorance of energy-saving considerations. Take roof overhangs, for example, which in warm climates 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

PRECEDING PAGES: MATT VINCENT ILLUSTRATION; JOEY NIGH *Corbis* (*London*); LIOR RUBIN *Peter Arnold, Inc.* (*Jerusalem*); K. L. NG (*Malaysia*); DANIELA MAC ADDEN (*Buenos Aires*); ABN-AMRO (*Amsterdam*); SZENCORP (*Melbourne*); GENZYME (*Cambridge, Mass.*); JOERG BOETHLING *Peter Arnold, Inc.* (*Hamburg*)



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

Energy End-Use Efficiency. Eberhard Jochem in *World Energy Assessment 2000*, Chapter 6. UNDP/WEC/UNDESA, 2000.

Steps towards a Sustainable Development: A White Book for R&D of Energy-Efficient Technologies. Edited by Eberhard Jochem. CEPE and Novatlantis, March 2004. www.cepe.ethz.ch

Experience with Energy Efficiency Policies and Programmes in IEA Countries. Howard Geller and Sophie Attali. International Energy Agency, 2005.