

SCIENTIFIC AMERICAN

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 CO₂ 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 (CO₂). Ever more people are convinced that prudence dictates a reversal of the present course of rising CO₂ 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 CO₂ 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 disappear-

ance of the Greenland ice cap. Two years ago the two of us provided a simple framework to relate future CO₂ 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 CO₂ 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 opposite page].

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

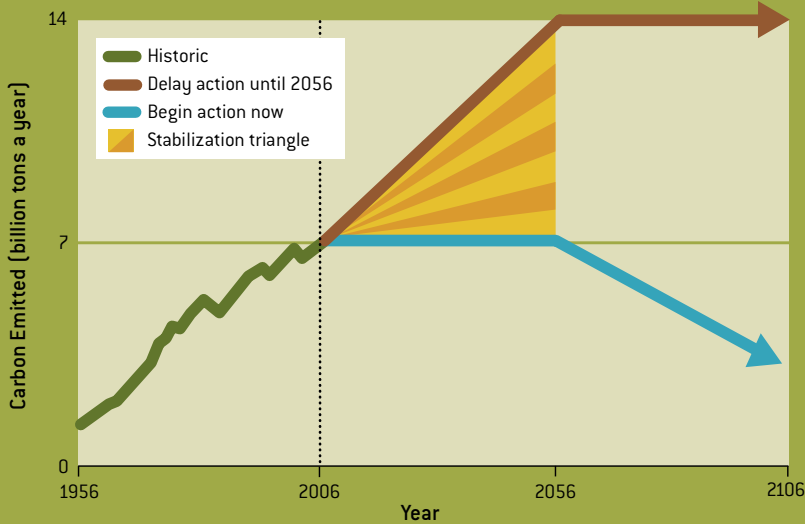
MANAGING THE CLIMATE PROBLEM

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.

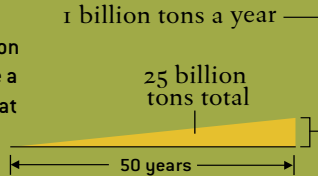
ANNUAL EMISSIONS

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.



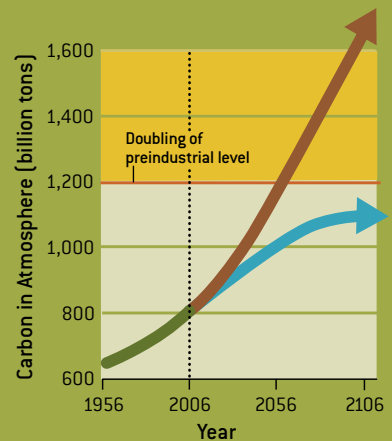
THE WEDGE CONCEPT

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 CO₂ 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 CO₂ 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-

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 opposite 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 CO₂ 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

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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.

Efficiency in electricity use is the most obvious substitute for coal. Of the 14 bil-

lion 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 CO₂ 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 CO₂ 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 CO₂. To achieve one wedge, utilities need to equip 800 large coal plants to capture and store nearly all the CO₂ otherwise emitted. Even in a carbon-constrained world, coal mining and coal power can stay in business, thanks to carbon capture and storage.

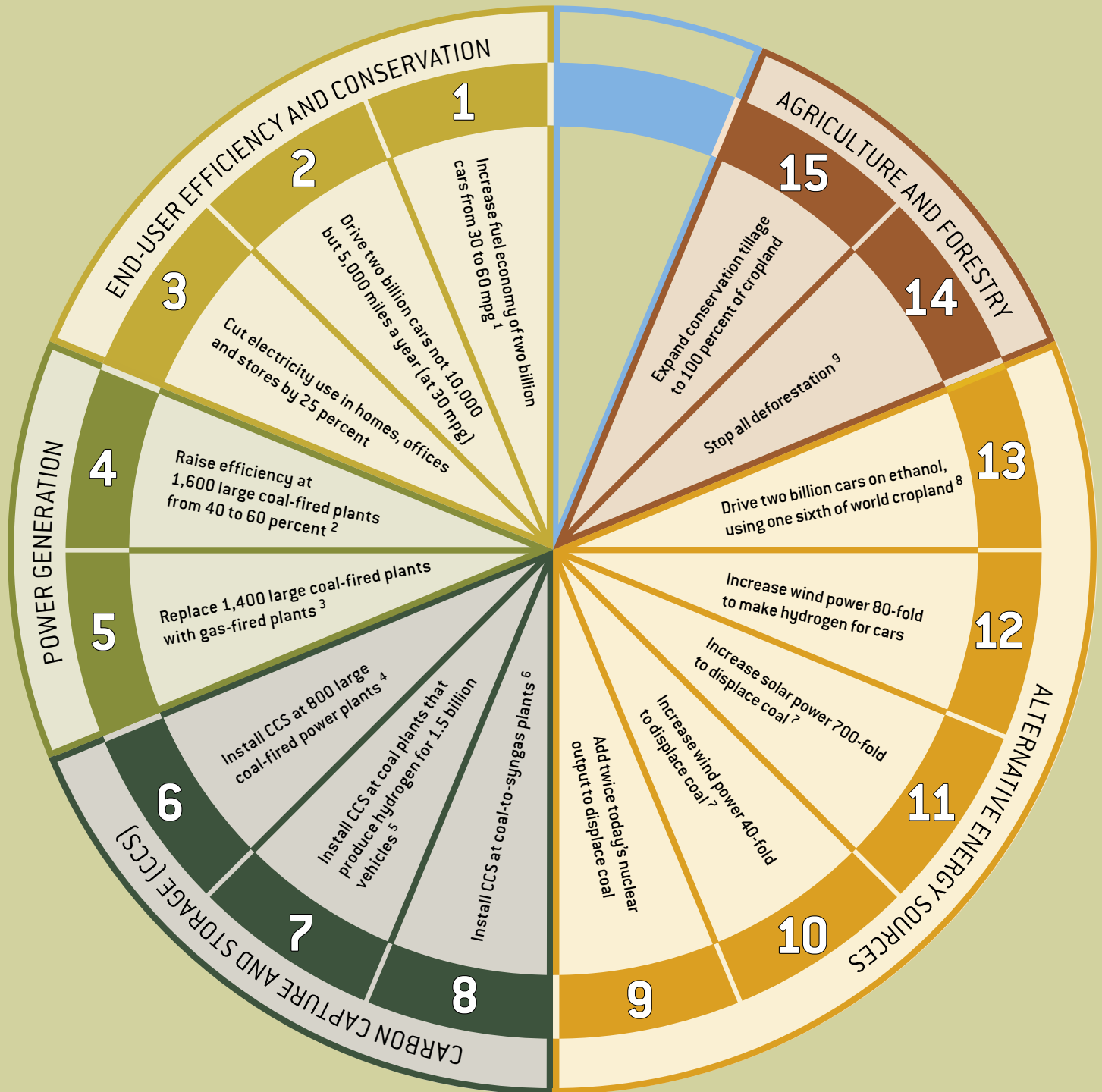
The large natural gas power plants operating in 2056 could capture and store their CO₂, too, perhaps accounting for yet another wedge. Renewable and nuclear energy can contribute as well. Renewable power can be produced from sunlight directly, either to energize photovoltaic cells or, using focusing mirrors,

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15 WAYS TO MAKE A WEDGE

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



Notes:

- ¹ World fleet size in 2056 could well be two billion cars. Assume they average 10,000 miles a year.
- ² "Large" is one-gigawatt (GW) capacity. Plants run 90 percent of the time.
- ³ Here and below, assume coal plants run 90 percent of the time at 50 percent efficiency. Present coal power output is equivalent to 800 such plants.
- ⁴ Assume 90 percent of CO₂ 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 syngas 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.

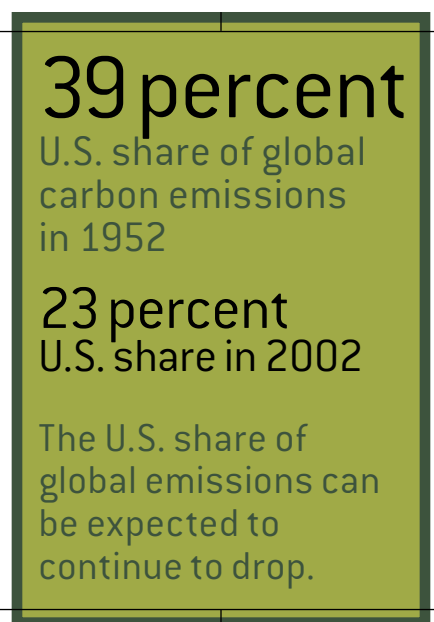
to heat a fluid and drive a turbine. Or the route can be indirect, harnessing hydro-power and wind power, both of which rely on sun-driven weather patterns. The intermittency of renewable power does not diminish its capacity to contribute wedges; even if coal and natural gas plants provide the backup 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 de-

carbonized 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 secu-



urity, 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 CO₂ 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 CO₂ at synfuels plants might well produce a wedge.

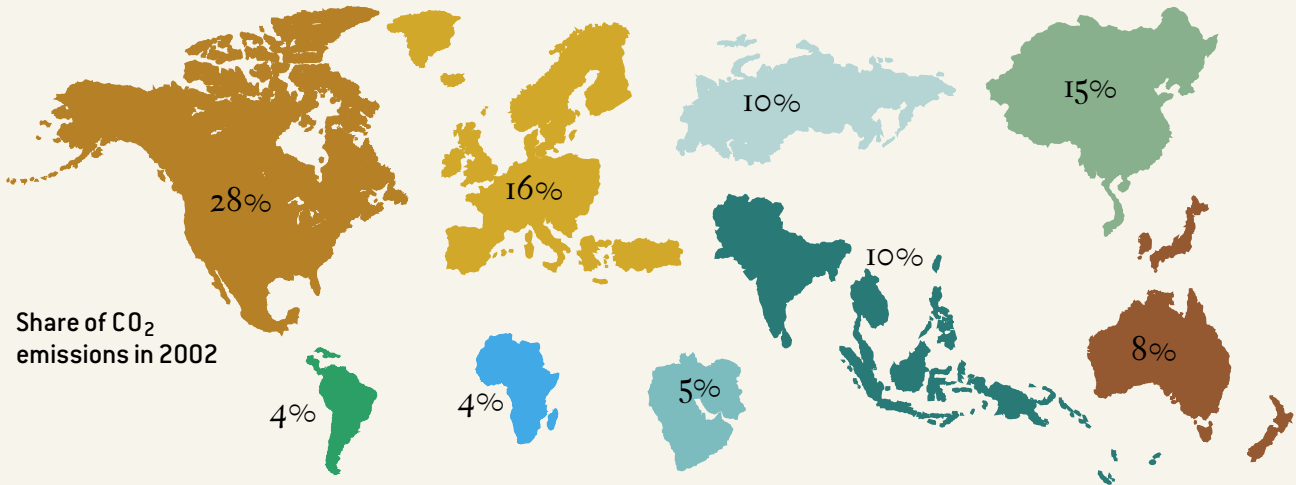
Not all wedges involve new energy technology. If all the farmers in the world practiced no-till agriculture rather than conventional plowing, they would contribute a wedge. Eliminating deforestation would result in two wedges, if the alternative were for deforestation to continue at current rates. Curtailing emissions of methane, which today contribute about half as much to greenhouse warming as CO₂, 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

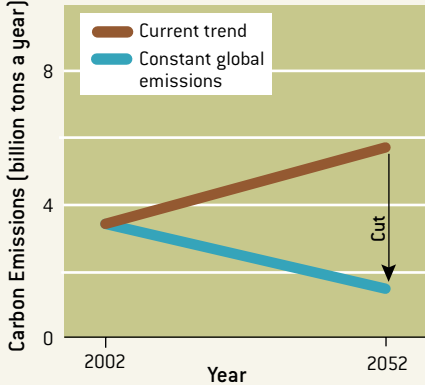
WHAT SET OF POLICIES will yield seven wedges? To be sure, the dramatic changes we anticipate in the fossil-fuel system, including routine use of CO₂ capture and storage, will require institutions that reliably communicate a price for present and future carbon emissions. We estimate that the price needed 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 CO₂ 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 CO₂ 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 CO₂.) 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

RICH WORLD, POOR WORLD

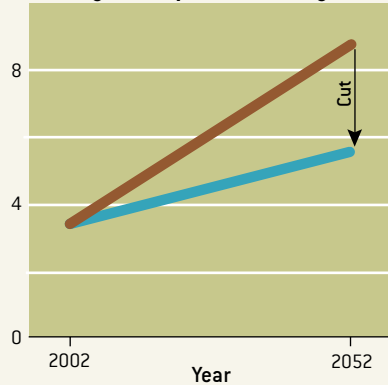
To keep global emissions constant, both developed nations (defined here as members of the Organization for Economic Cooperation and Development, or OECD) and developing nations will need to cut their emissions relative to what they would have been (arrows in graphs below). The projections shown represent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



To hold global emissions flat, the OECD must emit less than today ...



... to let non-OECD nations emit more as they develop economically



OECD

- North America and Mexico
- Europe
- East Asia and Oceania

NON-OECD

- South/Southeast Asia
- Africa
- East Asia
- Former Soviet Bloc
- West Asia
- Central America and South America

kilowatt-hour of electricity from coal.

But a price on CO₂ 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 CO₂ 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 CO₂ 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

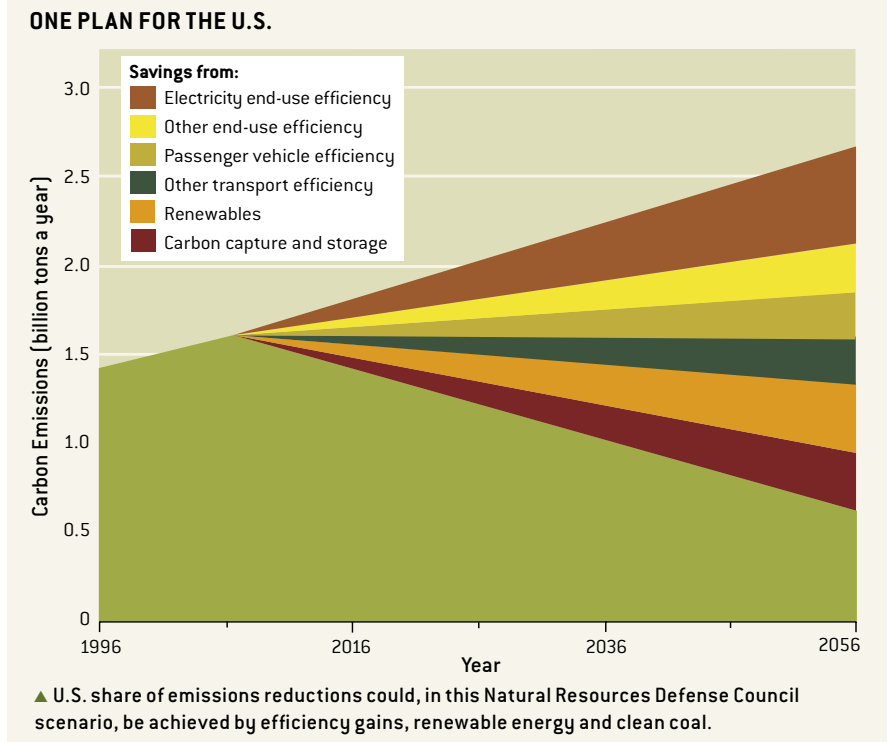
was articulated in 2003 by Prime Minister Tony Blair—namely, a 60 percent reduction by 2050, relative to recent levels. The non-OECD countries could then emit 60 percent more CO₂. On average, by midcentury they would have one half the per capita emissions of the OECD countries. The CO₂ output of every 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.

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 CO₂ 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 CO₂ 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

Princeton University 

CMI Graphics by Douglas Jakobsen



Carbon Mitigation Initiative
Princeton Environmental Institute
Princeton University
www.princeton.edu/~cmi

Three percentages on the map on p. 6 in this reprint differ slightly from those in the September 2006 issue on p. 56.
The percentages in this reprint are correct. An erratum will appear in a later issue of *Scientific American*.