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SOLVING THE CLIMATE PROBLEM

Technologies Available to Curb CO_2 Emissions

by Robert Socolow, Roberta Hotinski, Jeffery B. Greenblatt, and Stephen Pacala

The atmosphere's concentration of carbon dioxide (CO_2) has increased by more than 30 percent over the last 250 years, largely due to human activity. Two-thirds of that rise has occurred in the past 50 years.[1] Unless there is a change, the world will see much higher CO_2 levels in the future—levels that are predicted to lead to damaging climate change. Fortunately, many carbon mitigation strategies are available to set the world on a new path, one that leads to a lower rate of CO_2 emissions than is currently expected.

The environmental community is currently playing a prominent role in the development of the CO_2 policies that will elicit these strategies. Until a few years ago, the environmental community was almost exclusively interested in policies that promote renewable energy, conservation, and natural sinks. More recently, it has begun to explore alliances with traditional energy supply industries on the grounds that to establish the pace required to achieve environmental goals, parallel action on many fronts is required.

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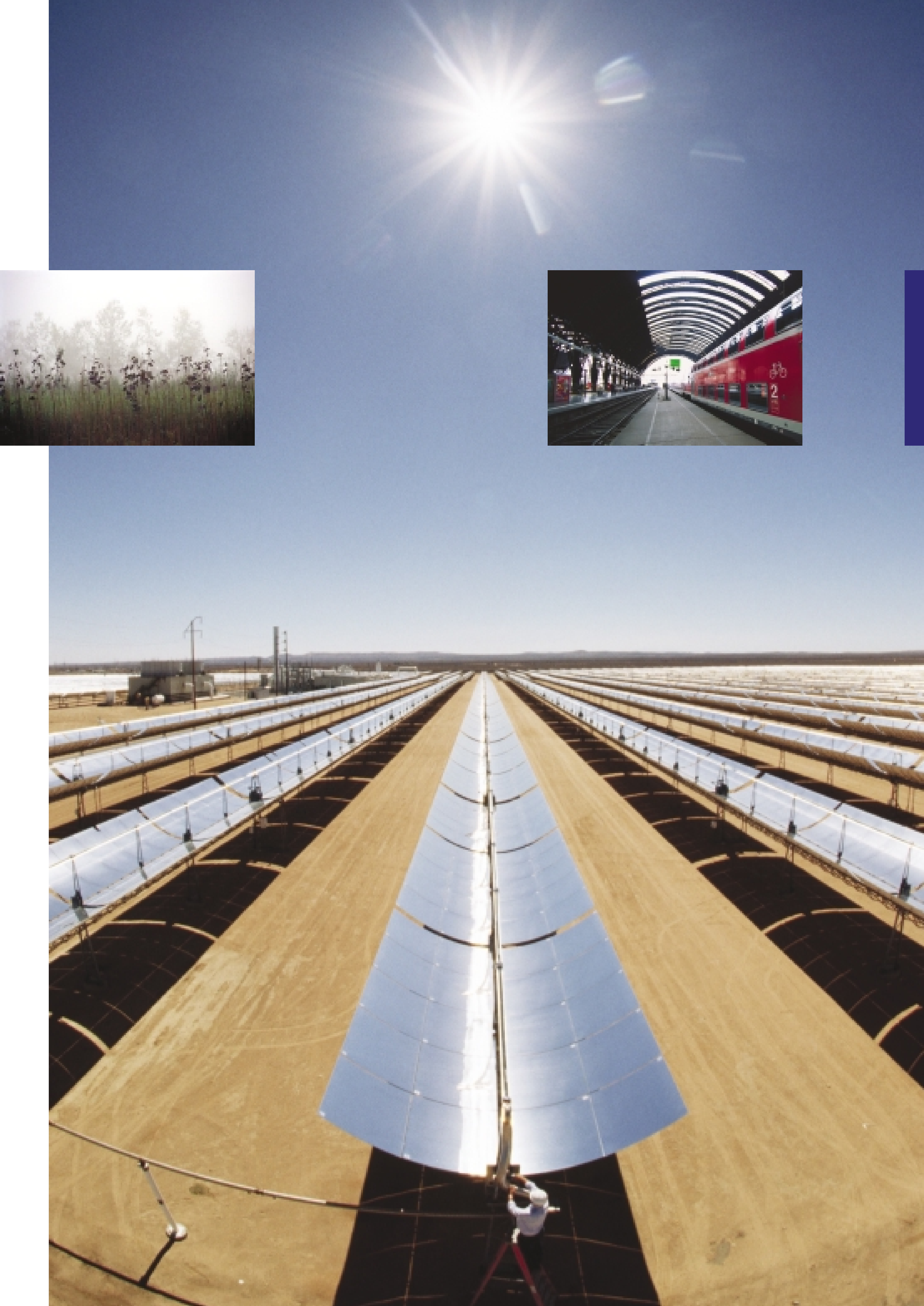
Charting a New Path

Comparing the carbon mitigation potential of different strategies requires a fixed time frame. A 50-year perspective may be best: It is long enough to allow changes in infrastructure and consumption patterns but short enough to be heavily influenced by decisions made today.

If the world continues on its currently predicted path for 50 years—relegating significant action on global carbon to a later time—many models of this future show CO_2 emissions from human activities roughly doubling by 2054 relative to today (see Figure 1a on page 11, dashed line).[2] This path is likely to lead to at least a tripling of the preindustrial (circa 1750) level of CO_2 in the atmosphere—280 parts per million (ppm)—by the middle of the next century.[3] Such a high concentration is likely to be accompanied by significant global warming, rising sea level, increased threats to human health, more frequent extreme weather events, and serious ecological disruption.[4]

An alternate 50-year future is a world in which emissions stay roughly flat (Figure 1a, solid line). Assuming natural sinks of carbon in the ocean and on land continue to function as they have in the past (see the box on pages 14 and 15), such a world can avoid a doubling (550 ppm) of the preindustrial CO_2 concentration if further emissions cuts are made after 2054. Avoiding a doubling of CO_2 levels is predicted to reduce substantially the likelihood of the most dramatic consequences of climate change, such as shut-



down of the ocean's thermohaline circulation (which transports heat from the equator to northern climes) and disintegration of the West Antarctic Ice Sheet.[5]

However, keeping global emissions at their current level will require a monumental effort. As seen in Figure 1a, committing to an emissions trajectory approximating the flat path entails an amount of CO_2 emissions reduction in 2054 roughly equal to all CO_2 emissions today.

In 2000, about 6.2 billion tons of carbon were emitted into the atmosphere as CO_2. Approximately 40 percent was emitted during the production of electricity and 60 percent when fuels were used directly in vehicles, homes, commercial buildings, and in industries. Approximately 55 percent was emitted in the 30 member countries of the Organisation for Economic Co-operation and Development (one quarter of the world's total in the United States), 10 percent in transitional economies (Russia and other formerly Communist countries), and 35 percent in developing countries.[6] To achieve the flat trajectory, therefore, no-carbon and low-carbon energy strategies must be implemented on a massive scale across all sectors of the economy and in countries at all stages of economic development.

The Scale of the Problem: Stabilization Wedges

To assess the potential of various carbon mitigation strategies, the concept of "stabilization wedges" is useful. The difference between the currently predicted path and the flat path from the present to 2054 gives a triangle of emissions to be avoided (see Figure 1a), a total of nearly 200 billion tons of carbon. This "stabilization triangle" can be divided into seven triangles—or "wedges"—of equal area (see Figure 1b on page 11). Each wedge results in a reduction in the rate of carbon emission of 1 billion tons of carbon per year by 2054, or 25 billion tons over 50 years.

Fifteen carbon-reduction strategies have been examined, each of which is based on known technology, is being implemented somewhere at an industrial scale, and has the potential to contribute a full wedge to carbon mitigation.[7] Scaling up from present capacity to an entire wedge would be challenging but plausible in each of the 15 cases. Each wedge would entail environmental and social costs that need to be carefully considered.

Expressing various strategies in terms of the amount of activity required to fill one wedge allows for comparisons across strategies: area of forest plantation versus number of fuel-efficient cars versus number of coal plants where carbon emissions are captured and stored (sequestered from the atmosphere), for example. The strategies may be grouped into five categories: energy conservation, renewable energy, enhanced natural sinks, nuclear energy, and fossil carbon management.

Energy Conservation

History leads one to expect substantial increases in energy efficiency in the future, even without an emphasis on cutting carbon emissions. Over the past 30 years, advances in efficiency, in conjunction with changes in the sources of energy supply, have led carbon emissions to grow only half as fast as the gross world product (1.5 versus 3 percent per year).[8] As a result, global carbon intensity—the ratio of global carbon emissions to gross world product—has been steadily falling. If the patterns of the past 30 years continue for another half century, the world carbon intensity will fall by half, relative to today. This reduction is already taken into account in the currently predicted path in Figures 1a and 1b. To count toward any wedge, changes in efficiency and all other strategies will need to result in an even lower carbon intensity than that expected from historical trends.

Global CO_2 emissions come from three broad end-use sectors: power generation (which in 2000 made up 42 percent of emissions), transportation (22 percent), and direct uses of fuel in industry and buildings (36 percent).[9] There are opportunities everywhere: in power plants and household appliances, in airplane engines and city planning, in steel mills and materials recycling. In a world focused on carbon, all three sectors will become targets of more intense efforts to improve energy efficiency.[10]

For example, a conspicuous source of a wedge is increased efficiency for the world's light-duty vehicles—cars, vans, sports utility vehicles (SUVs), and light trucks. A recent study by the global auto industry, the Sustainable Mobility Project (SMP),[11] reports that the world's light-duty vehicles emitted 0.8 billion tons of carbon as CO_2 in 2000, one-eighth of all global emissions. SMP predicts that these emissions will double in 2050, to 1.6 billion tons of carbon per year. In this scenario, while miles driven by light-duty vehicles increases 123 percent (1.52 percent per year), average fuel economy (miles per gallon) increases by only 22 percent (0.4 percent per year). Representative values yielding such carbon emissions in 2054, for example, are 1.6 billion light-duty vehicles (versus about 600 million today), 10,000 miles per year of driving per vehicle (about the same as today) and 30 miles per gallon average fuel economy (versus somewhat more than 20 miles per gallon today).

Almost a whole wedge is achieved (actually, 0.8 wedges) if 2054 fuel economy doubles, relative to what SMP projects, or if total distance driven in 2054 is half as much as SMP projects.[12] Such a reduction in driving could be accomplished by increased reliance on mass transit and telecommuting, if urban planning makes these options convenient and economical relative to travel in a private vehicle. Achieving a wedge here is approximately equivalent to keeping the total CO_2 emissions rate from the world's light-duty vehicles in 2054 no higher than today's instead of letting it roughly double.

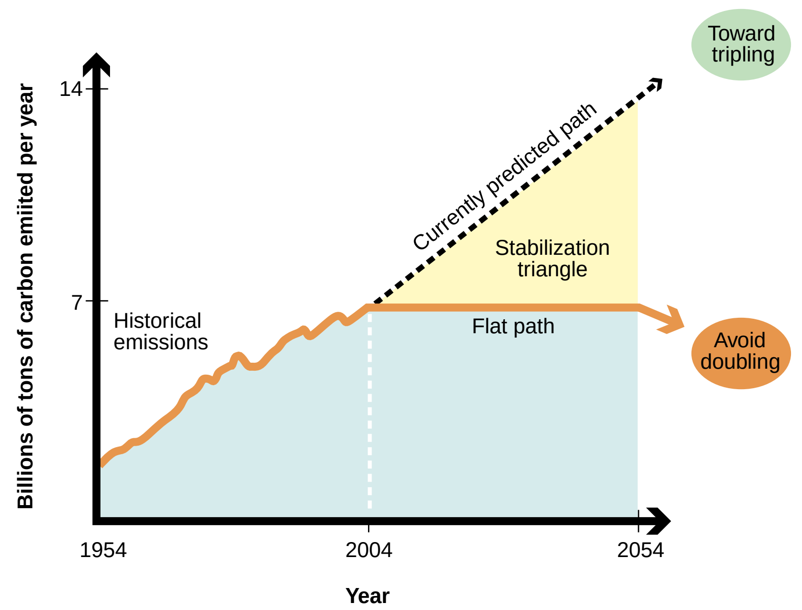
Another route to wedges of energy efficiency is adding a carbon focus to capital formation (such as new power plants, steel mills, and apartment buildings). Decisions that determine the energy efficiency of the world's capital stock are particularly important, because they lock in a particular level of energy efficiency for many decades.

For example, the details of the construction of an apartment building can dictate its future CO_2 emissions for a century; of a power plant, for a half century; of a truck, for a decade. Retrofitting an item of capital stock after construction is generally far more costly than making the item energy efficient in the first place.

At present, much of the world's addition to its capital stock is taking place in developing countries, a trend that is expected to remain true throughout the next 50 years. More aggressive programs to demonstrate low-carbon capital facilities—such as advanced power plants—in industrialized countries may reduce the reluctance of developing countries to build their own low-carbon capital facilities in parallel. New financial mechanisms that encourage globally coordinated demonstration of new low-carbon technologies are justified, because wherever capital facilities are built that are inappropriate for a future where global carbon emissions are constrained, the world bears the costs of their future emissions.

It is impossible to decide which improvements in energy efficiency will arrive only in a world focused on global carbon management and which will arrive regardless. For example, installing the most efficient lighting and appliances available, along with improved insulation, could supply two wedges of emissions reductions if applied in all new and existing residential and commercial buildings by 2054, provided one assumes that no such improvements would be installed without a carbon constraint. An Intergovernmental Panel on Climate Change (IPCC) report expects half of these reductions to arrive without climate policy, so it is conservative to expect energy efficiency improvements in buildings to yield at most one wedge, rather than two.[13] Similarly, compact fluorescent bulbs alone could provide one-fourth of a wedge over the next 50 years if used instead of incandescent bulbs—which are four times less efficient—for all the lighting projected for 2054.[14] Energy efficiency also carries

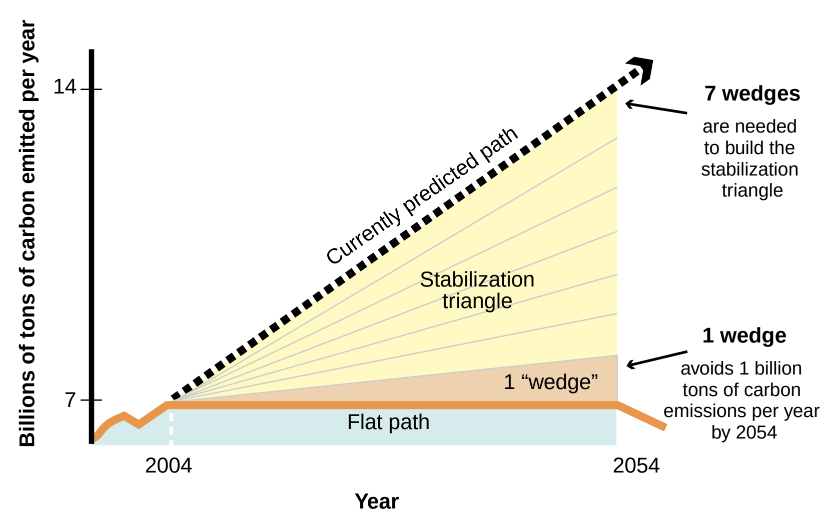
Figure 1a. Historical carbon emissions with two potential pathways for the future



NOTE: Our currently predicted path (dotted black line) will probably lead to at least a tripling of atmospheric carbon dioxide (CO_2) relative to its preindustrial concentration, while keeping emissions flat (solid line) would put us on track to avoid a doubling of CO_2.

SOURCE: R. Socolow, R. Hotinski, J. B. Greenblatt, and S. Pacala.

Figure 1b. Stabilization wedges



NOTE: The stabilization triangle in Figure 1a can be divided into seven equal "wedges" that represent activities capable of reducing one billion tons of carbon per year by 2054.

SOURCE: R. Socolow, R. Hotinski, J. B. Greenblatt, and S. Pacala.

intangible benefits in addition to financial savings: It fosters elegant design, quality construction, and careful maintenance that result in more satisfying products.

Energy efficiency does not have to do the whole job of keeping global carbon emissions constant for the next 50 years. There is room for energy use to grow, even when carbon emissions are constant, as long as the growth is in the form of no-carbon and low-carbon energy. In particular, the prospect of a future much more fully powered and fueled by renewable energy is tantalizing.

Renewable Energy

A useful division of CO_2 emissions distinguishes those arising at power plants and those arising where fuels are used directly. The introduction of renewable energy can reduce emissions in both settings.

Renewable Electricity

Electricity can be produced by many renewable energy sources. Hydropower was the first renewable energy source to gain a large market share. Now, wind power—growing globally for the past decade at about 30 percent per year—is playing a substantial role in several countries, notably Germany and Denmark. Solar photovoltaic electricity (PV), from a much smaller base, is also growing 30 percent per year globally.

A wedge from renewable electricity replacing coal-based power is available from a 50-fold expansion of wind by 2054 or a 700-fold expansion of PV relative to today. The expansion factor for geothermal energy is about 100. Tidal energy and wave energy are probably too untested at a large scale for a claim to be made for a wedge based on existing technology.

A 50-fold expansion of wind amounts to deploying two million wind turbines (of the one-megawatt size that is currently typical).[15] The land demands are considerable: A wedge of wind requires deployment on at least 30 million hectares (the area of the state of Wyoming or nearly the area of Germany). Because wind turbines slow down the wind, the wind turbines on a wind farm are typically separated by 5 to 10 rotor diameters to make room for the wind speed to recover from one wind turbine to the next. Current rotor diameters are approaching 100 meters, so one should expect perhaps two wind turbines per square kilometer, or five per square mile. The spaces between turbines on land can be used in many ways, including for agriculture and grazing.

Nonetheless, because modern wind turbines are so tall (as tall as all but the very tallest skyscrapers) and therefore visible from far away, the expansion of wind farms is already provoking strong NIMBY (not in my backyard) reactions. In response, wind farms in Europe, where wind power is expanding most rapidly, are being taken to offshore locations—recently, far enough to be invisible from the shore.[16]

For a renewable energy technology, land demands for PV are relatively low because the efficiency of conversion of sunlight to PV is relatively high: An entire wedge of PV electricity will require an estimated two million hectares (the area of New Jersey).[17] Some of this area can be supplied by the roofs and walls of buildings. The only technology comparable in efficiency of conversion of sunlight is the solar engine running on high-temperature heat, produced by a solar concentrator (a focusing trough or dish). This technology was commercialized for a brief time not very long ago with the help of subsidies and will probably return.

Wind, PV, and solar thermal energy all have the obvious problem of intermittency. The output of wind turbines is highly dependent on the strength of the wind, and solar cells and solar troughs provide electricity only when the sun shines. This problem grows more acute as these intermittent technologies gain market share. To be practical for large-scale use in electrical grids, intermittent renewable energy sources are best combined with energy storage technologies as well as energy supply technologies that can fluctuate in output yet can also operate a large fraction of the time. Natural gas turbines are well

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Although the land demands associated with a wedge from wind power are considerable (30 million hectares—the area of Wyoming), land between turbines can be used for agriculture, grazing, and other purposes.

matched to intermittent renewables, as is hydropower.

Renewable Fuels

There are fewer routes to low-carbon fuels than to low-carbon electricity. Renewable biofuels can be produced from vegetation, and hydrogen—a no-carbon fuel—can be produced from renewable electricity.

Because plant matter is created by photosynthesis using CO_2 from the atmosphere, combustion of "biofuels" simply returns borrowed carbon to the atmosphere. Renewability requires that the plants are grown sustainably—that is, planting must keep pace with harvesting—so that there is no net effect on the CO_2 concentration of the atmosphere. Renewability also requires that very little fossil fuel is used in harvesting and processing. Renewable biofuels can displace the gasoline for a car or the cooking fuel for a stove.

The world's two largest biofuels programs today are the Brazilian program to produce ethanol from sugar cane and the U.S. program to produce ethanol from corn. Between them, the two programs make a total of 22 billion liters of ethanol per year.[18] If the world's ethanol production could be increased by a factor of about 50, with much less associated fossil fuel use, this strategy could provide enough renewable fuel to account for one wedge of the stabilization triangle, assuming that ethanol displaces gasoline. The land demands, however, would be much greater for a wedge of biofuel than for a wedge of PV or even a wedge of wind—about 250 million hectares,[19] an area almost the size of India and one-sixth of the area now used globally for all crops. Bioengineering might increase the efficiency of plant photosynthesis, but large-scale production of biofuels will always be a land-intensive proposition.

Wind and PV can also be used to produce hydrogen fuel, enabling an economy where hydrogen is the dominant fuel (the "hydrogen economy"). The attractiveness of a hydrogen economy, from a global carbon perspective, stems from the simple fact that hydrogen (H_2), unlike almost every other combustible gas or liquid today considered a usable fuel, does not contain carbon. When conventional fuels are used in individual cars, trucks, or buildings, CO_2 is produced at such small scale that recovery of CO_2 is, if not hopeless, then extremely costly. Substantially reducing the CO_2 emissions associated with energy use in vehicles and buildings, therefore, requires replacing carbon-containing fuels either with hydrogen or, in some cases, electricity.

For hydrogen fuels to contribute a wedge, they cannot be produced by processes that emit as much CO_2 as would fossil fuels with the same energy content. Producing hydrogen by electrolysis after producing electricity from wind emits no CO_2, while producing hydrogen from natural gas or coal—the principal primary fuels used to make hydrogen today—ordinarily emits such large amounts of CO_2 as to defeat the emissions-reduction objective. Producing hydrogen from fossil fuels can lead to substantially reduced CO_2 emissions (relative to the emissions from the hydrocarbon fuel displaced) only if the CO_2 emissions can be captured and stored (discussed below).

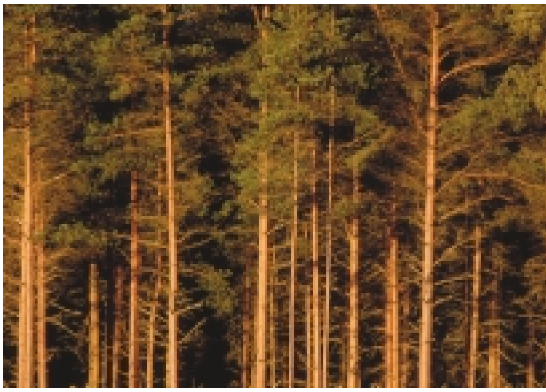
One can compare the relative impact on carbon emissions of using a given amount of renewable electricity to back out conventional coal-based electricity or to back out gasoline via the intermediate step of hydrogen production by electrolysis. Because the production of hydrogen requires extra energy, and because the carbon content of coal is high, displacing coal-based electricity with wind electricity provides emissions reductions roughly twice as great as displacing gasoline with wind-produced hydrogen fuel.[20] Thus, from a climate perspective, the optimal use of wind may not be as a primary energy source for hydrogen.

Enhanced Natural Sinks

The strategy of compensating for CO_2 emissions by deliberately enhancing natural sinks challenges our capacity to use large areas of land in ways that are not damaging to biodiversity. (See the box on pages 14 and 15 for futher discussion of natural sinks.) Enhancing natural sinks entails fostering the biological absorption of carbon and increasing its storage above and below the ground by, for example, reducing deforestation, creating new forest plantations on non-forested land, or expanding conservation tillage.

Current deforestation is transferring carbon from forests to the atmosphere at a rate of approximately one billion tons of carbon per year (a rate that is still very uncertain). If we arbitrarily assume that today's deforestation rate declines by 50 percent over the next 50 years in a world that does not pay attention to carbon issues, a half-wedge could be provided by halting deforestation completely in that time. Another half-wedge could be provided by establishing plantations on 300 million hectares of non-forested land worldwide—about the same area needed to supply a whole wedge of biofuels (see above) and five times the land area now in tropical plantations.[21]

Conversion of natural vegetation to annually tilled cropland has resulted in the loss of more than 50 billion tons of carbon from the world's soils over historical time.[22] Conservation tillage, by which farmers avoid aeration of the soil to promote retention of carbon, could provide a full wedge, if used on all cropland around the globe; today, less than one-tenth of agricultural produc-



Natural carbon sinks can be enhanced by creating forest plantations, such as this pine stand in Angus, Scotland.

tion uses conservation tillage.[23] The increased need for weed control that accompanies conservation tillage can generate its own environmental problems. However, conservation tillage can be implemented in many ways, ranging from heavy use of chemical herbicides to planting cover crops immediately after harvest, with little or no herbicide use.

Nuclear Energy

Those hoping for a revival of nuclear power see support coming their way if carbon management becomes a higher societal priority. Yet in environmental discourse, nuclear power is quite often not mentioned.

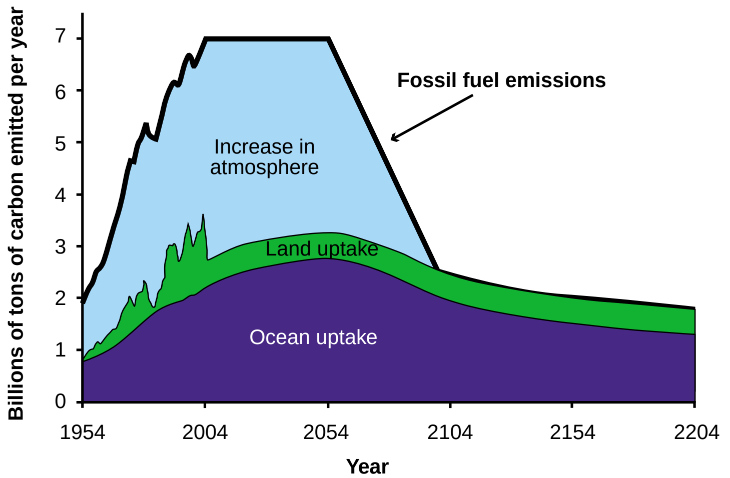
The connection between nuclear power and reduced carbon emissions is likely to become an important part of the debate about the extension of the

OCEAN AND LAND SINKS

The oceans and terrestrial ecosystems have historically slowed the rise of atmospheric carbon dioxide (CO_2), absorbing more than half of the carbon that has been emitted into the atmosphere since the start of the Industrial Revolution. The figure below depicts fossil fuel emissions, atmospheric growth, and the ocean and land sinks for the past 50 years and a projection for the next two centuries that stabilizes atmospheric CO_2 at 500 parts per million (ppm). The flat path shown in Figures 1a and 1b is assumed for the years 2004–2054.

The future contributions of the land and ocean sinks, however, will be affected by changes in climate and other factors. Changes in these natural sinks could change the size of emissions reductions needed for stabilization by up to three wedges in either direction.

Where does the carbon go?



NOTE: Shown are total fossil fuel emissions (thick black line), atmospheric increase (light blue), land uptake (green), and ocean uptake (dark blue). The atmospheric increase is the difference between fossil-fuel emissions and ocean and land sinks. The ocean sink is calculated with a simple model (see source below), and the land sink is held constant after 2004 at 0.5 billion tons of carbon per year. Fossil-fuel emissions are prescribed by a 500 parts per million stabilization path with the following four components: 1954–2004: historical emissions; 2004–2054: flat path emissions, as in Figures 1a and 1b; 2054–2104: linear descent to stabilization; after 2104: stabilization. "Stabilization" means there is no further build-up of CO_2 in the atmosphere, because emissions are balanced by land and ocean sinks.

SOURCE: R. Socolow, R. Hotinski, J. B. Greenblatt, and S. Pacala. The ocean sink is calculated using a model described in U. Siegenthaler and F. Joos, "Use of a Simple Model for Studying Oceanic Tracer Distributions and the Global Carbon Cycle," *Tellus* 44B (1992): 186–207.

Oceans

Over the past two centuries, the oceans have absorbed roughly half of the 250 billion tons of carbon that have been emitted from fossil fuel combustion.[1] For the past 20 years, the oceans have been absorbing almost two billion tons of carbon per year as CO_2, and the rate is steadily increasing. Complete ocean mixing takes more than a thousand years, so the continual upwelling of deep water with preindustrial CO_2 concentrations will allow the ocean to be a significant sink of atmospheric CO_2 for several centuries. In the figure at left, the ocean sink is shown to increase until 2054 and then to fall gradually under the depicted fossil fuel emissions scenario.

The 50-year future of the ocean sink is uncertain by about two wedges—50 billion tons of carbon over 50 years—in either direction. The uncertainty is the result of limitations in the accuracy of historical data, modeling of interannual ocean variability, interactions of marine organisms with the carbon cycle, and regional mixing, particularly in the Southern Ocean.[2]

Climate-change feedback compounds this uncertainty. If emissions are flat over the next 50 years, the ocean sink will almost certainly continue to increase its carbon uptake from the atmosphere. However, there is a chance that climate change will weaken the ocean sink, substantially increasing the CO_2 emissions reductions needed for stabilization at 500 ppm. While the ocean's response to warming is not well understood, the fact that the solubility of CO_2 in the ocean decreases as the ocean temperature plant life of existing reactors. If, over the next 50 years, all of today's nuclear power plants were to be phased out in favor of modern coal plants, about half a wedge of additional CO_2 emissions reductions would be required to compensate. This half-wedge would not be required if current nuclear reactors were replaced with new ones, one-for-one.

Similarly, building a wedge with new nuclear power requires tripling the current nuclear electricity production, assuming the new plants displace coal. This would mean building about 700 new 1,000-megawatt nuclear plants around the world.[24]

The expansion of nuclear power is, of course, a politically charged issue. Much of the debate has focused on plant safety and waste management. The nuclear power community would welcome the opportunity to build a new generation of advanced nuclear reactors whose designs incorporate intrinsic safety features that

increases points to a weakening of the sink. This effect, not included in the model behind the figure, could be as much as one wedge.[3] Further, if global warming triggers a slowdown of the ocean's "conveyor belt"—the thermohaline circulation that transfers cold CO_2-rich surface waters to the deep ocean—this could further reduce carbon uptake, perhaps significantly. However, such a slowdown would require warming of several degrees Celsius that is unlikely to occur by 2054.[4]

The continued influx of CO_2 to the ocean will change ocean chemistry. Addition of CO_2 to the ocean makes it more acidic. Anthropogenic CO_2 emissions have already decreased surface-ocean pH by approximately 0.1 unit globally, comparable (though opposite in sign) to the pH change during the last ice age.[5] Increasing acidity may adversely affect marine ecosystems and alter the balance of dissolved minerals.[6] Addition of CO_2 to the ocean also reduces the concentration of carbonate, the ocean's main buffering agent, and will affect the ocean's ability to absorb CO_2 on long time scales.[7]

Land

The terrestrial biosphere, in contrast to the ocean, has been almost neutral with respect to carbon exchange, neither a significant net carbon source nor sink, when averaged over the past two centuries.[8] Prior to about 1950 it was a net source due to widespread land clearing for agriculture, but it has since become a net sink due to a variety of factors. These include regrowth on the previously cleared land, fire suppression (which increases the amount of carbon in standing wood), entombment of carbon in sediments of reservoirs and other bodies of water, the buildup of wood products in buildings and landfills, agricultural soil conservation, and, possibly, fertilization of vegetation by the increased CO_2 in the atmosphere or nitrogen in air pollution. Data show that for the past half century these factors have been taking more carbon out of the atmosphere than has been emitted to the atmosphere by the massive forest clearing in the tropics.[9] The net terrestrial sink over the past two decades has been somewhat less than half as strong as the net ocean sink.[10]

The future land sink depends on the relative importance of such mechanisms, which are still uncertain. For example, if the sink is caused primarily by regrowth on previously cleared land and fire suppression, then it will probably decrease over time as regrowth nears completion and as lands under fire suppression complete their adjustment to the new conditions.[11] This decrease, along with other possible negative impacts on the land sink due to changes in temperature and precipitation, could mean another two wedges of emissions reductions would be required for stabilization at 500 ppm CO_2. Some models predict that regional shifts to hotter and drier climates will dominate the future of the terrestrial sink and cause a catastrophic loss of global biodiversity and carbon.[12]

In contrast, if the sink is caused primarily by CO_2 fertilization, then it will increase with the buildup of atmospheric CO_2 to absorb three billion tons or more of carbon per year by mid-century.[13] This last mechanism represents the single-largest uncertainty for carbon management in the 50-year time frame—3 wedges' worth of uptake that could significantly reduce emissions cuts needed. The figure on page 14 is based on the assumption that the net land sink will remain approximately the same size as it has been over the last two decades, at half a billion tons of carbon per year, for the indefinite future.

All these considerations mean the future of the land sink is quite uncertain, ranging from uptake surpassing that of the ocean to a significant loss of carbon.

1. C. L. Sabine et al., "The Oceanic Sink for Anthropogenic CO_2," *Science*, 16 July 2004, 367–71.

2. C. Le Quéré and N. Metzl, "Natural Processes Regulating the Ocean Uptake of CO_2," in C. B. Field and M. R. Raupach, eds., *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World* (Washington, DC: Island Press, 2004).

3. J. B. Greenblatt and J. L. Sarmiento, "Variability and Climate Feedback Mechanisms in Ocean Uptake of CO_2," in Field and Raupach, ibid.

4. J. L. Sarmiento and C. Le Quéré, "Oceanic Carbon Dioxide Uptake in a Model of Century-Scale Global Warming," *Science*, 22 November 1996, 1346–50.

5. K. Caldeira and M. E. Wickett, "Anthropogenic Carbon and Ocean pH," *Nature*, 25 September 2003, 365.

6. U. Riebesell et al., "Reduced Calcification of Marine Plankton in Response to Increased Atmospheric CO_2," *Nature*, 21 September 2000, 364–67; and B. A. Seibel and P. J. Walsh, "Potential Impacts of CO_2 Injection on Deep-Sea Biota," *Science*, 12 October 2001, 319–20.

7. I. C. Prentice et al., "The Carbon Cycle and Atmospheric Carbon Dioxide," in J. T. Houghton et al., eds., *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

8. Sabine et al., note 1 above.

9. Prentice et al., note 7 above; and R. A. Houghton, "Why are Estimates of the Terrestrial Carbon Balance so Different?" *Global Change Biology* 9 (2003): 500–09.

10. Sabine et al., note 1 above.

11. G. C. Hurtt et al., "Projecting the Future of the U.S. Carbon Sink," *Proceedings of the National Academy of Sciences* 99 (1999): 1389–94.

12. P. M. Cox et al., "Acceleration of Global Warming Due to Carbon-Cycle Feedbacks in a Coupled Climate Model," *Nature*, 9 November 2000, 184–87.

13. J-L. Dufresne et al., "On the Magnitude of Positive Feedback between Future Climate Change and the Carbon Cycle," *Geophysical Research Letters* 29 (2002): doi: 10.1029/2001GL013777.

make minor events far less likely to escalate into major releases of radioactivity. Workable long-term nuclear waste management probably requires the development of a political consensus in favor of changing the objective from management by passive barriers to management actively and indefinitely.

Even more challenging than waste management, however, are the problems for international relations generated by the linkages between the military atom and the civilian atom. A climate strategy based on the expansion of nuclear power must contend with the need to reduce CO_2 emissions all over the world. Is the world ready to permit nuclear power development in all countries? Currently, the nuclear power program in Iran is a source of international tension: Although Iran claims its nuclear program is for peaceful purposes only and is willing to accept international safeguards, it appears determined to build a uranium-enrichment capability that would put it very close to nuclear weapons if it chose to go that route. Entirely new international arrangements that make unprecedented demands on the sovereignty of all countries are probably required for wedges of nuclear power to materialize.

The "mutual hostage" relationship among nuclear power plants creates yet another obstacle to the creation of a wedge of nuclear power. A reactor accident at any power plant generates political pressure for the shutdown of all power plants, to an extent not present elsewhere in the energy system.

Nuclear power does not have to play a major role in reducing global CO_2 emissions. Nuclear power addresses, for now, only the 40 percent of CO_2 emissions associated with electricity production. (Someday, perhaps, nuclear reactors will also produce hydrogen fuel.) To decarbonize electricity, there are many alternatives. As providers of low-carbon electricity, wedges of nuclear power compete with wedges of wind and PV, and, as well, with wedges from the fossil energy strategies.

Fossil-Carbon Management

In the flat trajectory of Figures 1a and 1b, fossil fuels hardly disappear in the next 50 years; rather, their CO_2 emissions stay constant. In that same period, however, global energy demand is predicted to grow even faster than global CO_2 emissions, more than doubling. If the flat trajectory is followed, the fossil fuel industry's share of the global energy system in 2054 will be much less than its 85 percent share today. How much less will be determined by the extent to which the CO_2 emissions to the atmosphere associated with fossil fuels can be reduced.

Fossil fuel CO_2 emissions can be reduced in two ways. The first strategy is to change the relative market shares of coal, oil, and gas. The second strategy is to interfere with the CO_2 emission process, preventing the CO_2 from reaching the atmosphere.

Changing the Mix of Fossil Fuels

Shifts in the market shares of coal, oil, and natural gas have been a feature of fossil fuels throughout their history. Carbon concerns have had only a minute role thus far in these shifts, but such concerns have formidable implications for the future. Each fossil fuel has its own ratio of hydrogen to carbon. Carbon emissions per unit of energy content are highest for hydrogen-poor coal and lowest for hydrogen-rich natural gas. (Carbon emissions per unit of energy content are approximately in the ratio of 5 to 4 to 3 for coal, oil, and natural gas, respectively.) Carbon concerns, as they come into play, will therefore favor natural gas and thwart coal. Greater-than-expected expansion in the global use of natural gas, which emits half as much CO_2 as coal for the same amount of electricity production, is a possible consequence of a carbon constraint.

Any major expansion of natural gas use will require transporting large amounts over long distances, either in liquefied form or in pipelines. A wedge's worth of power from natural gas instead of coal is matched to 50 large liquefied natural gas (LNG) tankers docking and unloading every day or building the equivalent of the Alaskan natural gas pipeline, currently under negotiation, every year.[25]

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Acid-gas injection wells in Alberta, Canada (near right), as a sulfur disposal strategy, co-store hydrogen sulfide and carbon dioxide. Studying cement seals in old wells (far right) clarifies risks of CO_2 leakage underground.

Carbon Capture and Storage

The second principal strategy for reducing the CO_2 emissions associated with fossil fuel use—interfering with CO_2 emissions—requires a two-step process known as "carbon capture and storage." The first step, carbon capture, typically creates a pure, concentrated stream of CO_2, separated from the other products of combustion. The second step, carbon storage, sends the concentrated CO_2 to a destination other than the atmosphere.

Opportunities for CO_2 capture are abundant. The natural gas industry routinely generates capturable streams of CO_2 when natural gas, after coming out of the ground, is stripped of CO_2 before shipment by pipeline or tanker. Refineries making hydrogen for internal use are generating, as a byproduct, capturable streams of CO_2; refinery hydrogen requirements, in turn, are increasing to process heavier crude oils and to remove more sulfur. Capturable streams of CO_2 will also be generated where technologies are deployed to convert coal or natural gas into liquid fuels, and the geopolitics and economics of oil are nearly certain to increase the use of these technologies. In a world focused on the reduction of CO_2 emissions, all these streams are candidates for capture, instead of venting to the atmosphere.

The most promising storage idea is "geological storage," in which the CO_2 is placed in deep sedimentary formations. (Alternate carbon storage ideas include storage of CO_2 deep in the ocean and storage of carbon in solid form as carbonates.) Carbon capture and storage has the potential to be implemented wherever there are large point sources of CO_2, such as at power plants and refineries. The storage space available below ground is probably large enough to make carbon capture and storage a compelling carbon mitigation option.

For decades, oil companies have been injecting CO_2 underground to scrub hydrocarbons from oil reservoirs in late stages of production, a tactic called enhanced oil recovery (EOR). Storing a wedge's worth of CO_2 would require scaling up the current global rate of injection of CO_2 in EOR by a factor of about 100.[26] Because EOR projects to date have not had the explicit objective of long-term CO_2 storage, little is known about the long-term fate of the CO_2 injected.

If waste carbon can be captured and stored, hydrogen production from coal and natural gas could provide an alternate route to the "hydrogen economy." And in all situations where CO_2 capture and storage is under consideration, there may be opportunities to "co-capture and co-store" other pollutants, like sulfur, with the CO_2. With co-capture, the costs of above-ground pollution control will be reduced, and perhaps pollution control costs and total environmental emissions will as well.

At this time, via demonstration projects, the carbon capture and storage strategy is undergoing its first testing (see the box on page 18). The environmental community is being asked to help establish the criteria—such as the conditions under which permits would be given for CO_2 storage below ground—to ensure that the strategy is effective and safe. Some in the environmental community want to keep their distance, calling carbon capture and storage an "addict's response" to climate change.[27] Others recognize the importance of taking part in setting the ground rules for carbon capture and storage to increase the attention paid to its environmental performance. Still others see benefit in engaging in coalition politics, leading to policies that advance several CO_2 mitigation strategies at once—to the benefit of technologies they prefer.

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Replacing burnt-out incandescent bulbs with fluorescent ones could be one of a handful of significant beginning steps toward reduced CO_2 emissions.

Getting Started with Wedges: The Next 10 Years

The challenges of carbon mitigation are daunting. Unless campaigns to reduce carbon emissions are launched in the immediate future across all sectors of the economy and in countries at every stage of economic development, there will be little hope of avoiding a doubling of atmospheric CO_2.

To clarify the scale of the effort, it is helpful to consider the emissions reductions needed over the next 10 years to stay on the flat path of Figures 1a and 1b, assuming the alternative is the currently predicted path. By 2014, as a point of reference, one might implement 20 percent of each of 7 wedges. There are many ways to do this.

• Addressing demand, to reduce electricity emissions, the world could accomplish the first 20 percent of a buildings efficiency wedge by replacing every burnt-out incandescent bulb with a compact fluorescent bulb. Addressing supply, the world could develop the first 20 percent of a wind wedge by completing 400,000 new wind turbines, or of a nuclear power wedge by building 140 new nuclear plants. It could implement CO_2 storage projects with 700 times the capacity of the Sleipner project (see the box on carbon capture and storage on page 18). As part of an augmented strategy to displace coal with natural gas in power plants, it could build 10 natural gas pipelines having the capacity of the Alaska pipeline now under discussion.

• To reduce transport emissions, again addressing demand, the world could improve average vehicle fuel economy by 25 percent with the assumption that the amount of driving also increases by 25 percent. Addressing supply, the world could convert 50 million hectares (200,000 square miles) to crops like sugar cane that can be converted to ethanol with modest fossil fuel inputs. It could accelerate the arrival of hydrogen-powered vehicles and the production of low-carbon hydrogen.

• To reduce emissions from the space-heating and -cooling of buildings, the world could embark on a campaign of implementing best-available design and construction practices, especially for new buildings but also for the retrofit of buildings.

• The world could take some pressure off the energy system by modifying the agricultural practices on nearly one-fifth of all cropland to bring about conservation tillage. It could create 60 million hectares of sustainable plantations on nonforested land and set a new course to eliminate tropical deforestation within 50 years.

It is hard not to feel overwhelmed by this menu. Are there ways out? Perhaps an optimum pace for a 50-year campaign would result in bringing some of these wedges forward more slowly, accomplishing less than 20 percent of the job in the first 10 years. But how much more slowly? Perhaps the number of parallel efforts can be reduced by getting two or three wedges from a single strategy; energy efficiency is the most likely area. But for many of the other strategies, bringing on two wedges is more than twice as hard as bringing on one because cheap and easy opportunities will be used up early on.

Perhaps the stabilization triangle will turn out to be smaller: The world economy might grow more slowly, and green plants, in response to elevated CO_2 levels, might store more carbon than predicted. But the stabilization triangle could just as easily be larger (see the box on pages 14 and 15). In this case, getting onto a path that avoids doubling the preindustrial CO_2 concentration might require more than seven wedges.

The Road Ahead

Advocates of any one wedge should take a clear-eyed look at the difficulties inherent in cutting one billion tons of carbon emissions per year using that strategy. Deep patterns in the energy system limit the rate of introduction of energy efficiency. Land-use constraints limit the roles of renewable energy and natural sinks. Deep fear and distrust, as well as nuclear weapons proliferation, hobble nuclear power. The long record of resistance to pro-environment initiatives by the fossil fuel industries compromises their credibility. Aesthetic considerations limit the penetration of several renewable options, including wind and hydropower.

Advocates of one kind of wedge should also not minimize its potential to attract the support of other interest groups who can help advance its adoption. The widespread use and economic competitiveness of natural gas and nuclear electricity mean they might be implemented within the existing energy system relatively quickly, bringing representatives from those industries to the table. Coal used with carbon capture and storage reduces not only CO_2 emissions but conventional pollution as well, a benefit attractive to public health advocates. Photovoltaics are bringing electricity to remote areas, including poor villages far from any electricity grid, and appeal to advocates for the developing world. Wind energy should engage rural communities, as it brings income to rural areas and may slow migration to cities. Biofuels and plantations can help reclaim degraded land, enhancing ecosystem services. The pursuit of energy efficiency will cut costs for businesses, providing joint environmental and economic gains. Attention to energy efficiency brings broad support from all who take pleasure in well-made goods.

CO_2 STORAGE PROJECTS

Environmental groups and others have called attention to the need to establish the long-term effectiveness of underground storage and its safety. Although CO_2 is not flammable or explosive, large CO_2 releases into low-lying depressions could lead to hazardous concentrations. CO_2 percolating upward from deep storage could also increase the acidity of ground water and soil.

Two major projects are under way to study geological CO_2 storage, each currently injecting one million tons of CO_2 per year. In the Weyburn project in Saskatchewan, Canada, CO_2 captured at a synthetic fuels plant in North Dakota and transported north to Saskatchewan by pipeline is used for enhanced oil recovery (EOR) in the aging Weyburn oil fields. In the Sleipner project in the North Sea off the coast of Norway, excess CO_2 in the natural gas being produced from one formation below the sea floor is stripped away and then reinjected into another reservoir, as opposed to the customary practice of venting it to the atmosphere. A third major project, the In Salah project in Algeria, is just starting. Like the Sleipner project, it will strip excess CO_2 from natural gas, and it will also store a CO_2 stream of about one million tons of CO_2 per year. In this project, the CO_2 will be injected into the formation from which the gas was initially recovered, aiding in gas recovery. This is in contrast to the Sleipner project, in which CO_2 is injected into a non-hydrocarbon-bearing formation.

This approach to carbon mitigation is very young and is still being reviewed by the international community. Next year, the Intergovernmental Panel on Climate Change (IPCC) will release a special report on carbon dioxide capture and storage (CCS) that will summarize current knowledge. If these initial findings and CCS pilot projects suggest that long-term storage will be safe and effective, and if adequate permitting procedures can be established, over the next 50 years CCS could provide one or more wedges of emissions reductions. For each CCS wedge, storage programs equivalent to 70 of the Sleipner, Weyburn, or In Salah projects would have to be created every year and maintained through 2054.

PHOTO COURTESY BP

At this facility in Algeria, excess CO_2 is removed from natural gas for injection underground.

A multiple-wedge approach to CO_2 policy will provide common ground and foster consensus on mitigation policy. Most advocates of particular wedges agree that it is too early now to settle on just a few "winner" strategies, that the relative attractiveness of strategies will differ from one region to another, that environmental problems associated with scale-up ought to be investigated, that subsidy of early stages is often merited, and that choices among mature alternatives should be determined mostly by market mechanisms. Framing the climate problem as one requiring the parallel exploration of many stabilization wedges may help broaden the political consensus for early action.

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NOTES

1. C. D. Keeling and T. P. Whorf, "Atmospheric CO_2 Records from Sites in the SIO Air Sampling Network," in Carbon Dioxide Information Analysis Center, *Trends: A Compendium of Data on Global Change* (Oak Ridge, TN: Ridge National Laboratory, 2000).

2. S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, 13 August 2004, 968–72.

3. R. Socolow, S. Pacala, and J. Greenblatt, "Wedges: Early Mitigation with Familiar Technology," to be published in the *Proceedings of GHGT-7, the 7th International Conference on Greenhouse Gas Control Technology, Vancouver, Canada, September 5–9, 2004* (forthcoming, 2004).

4. U. Cubasch et al., "Projections of Future Climate Change," in J. T. Houghton et al., eds., *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001), 525–82; and J. Antle et al., "Ecosystems and their Goods and Services," in J. J. McCarthy et al., eds., *Climate Change 2001: Impacts, Adaptation, and Vulnerability* (Cambridge, UK: Cambridge University Press, 2001), 235–342.

5. B. C. O'Neill and M. Oppenheimer, "Dangerous Climate Impacts and the Kyoto Protocol," *Science*, 14 June 2002, 1971–72.

6. International Energy Agency (IEA), *World Energy Outlook 2002* (Paris: Organisation for Economic Co-operation and Development/IEA, 2002), http://library.iea.org/dbtw-wpd/Textbase/nppdf/stud/02/weo2002_1.pdf.

7. Pacala and Socolow, note 2 above.

8. IEA, note 6 above.

9. IEA, note 6 above.

10. H. Geller, *Energy Revolution: Policies for a Sustainable Future* (Washington, DC: Island Press, 2003); and M. A. Brown, M. D. Levine, J. P. Romm, A. H. Rosenfeld, and J. G. Koomey, "Engineering-Economic Studies of Energy Technologies to Reduce Greenhouse Gas Emissions: Opportunities and Challenges," *Annual Review of Energy and the Environment* 23 (1998): 287–385.

11. World Business Council for Sustainable Development, *Mobility 2030: Meeting the Challenges to Sustainability, Full Report 2004* (Geneva, Switzerland: World Business Council for Sustainable Development, 2004), http://www.wbcsd.org.

12. Pacala and Socolow, note 2 above.

13. K. Blok et al., "Technological and Economic Potential of Greenhouse Gas Emissions Reduction," in B. Metz, O. Davidson, R. Swart, and J. Pan, eds., *Climate Change 2001: Mitigation* (Cambridge, UK: Cambridge University Press, 2001), 167–299.

14. Pacala and Socolow, note 2 above.

15. Pacala and Socolow, note 2 above.

16. See M. J. Pasqualetti, "Wind Power: Obstacles and Opportunities," *Environment*, September 2004, 22–38.

17. Pacala and Socolow, note 2 above.

18. IEA, *Biofuels for Transport: An International Perspective* (Paris: IEA, 2004).

19. Pacala and Socolow, note 2 above.

20. Pacala and Socolow, note 2 above.

21. Kauppi et al., "Technological and Economic Potential of Options to Enhance, Maintain, and Manage Biological Carbon Reservoirs and Geo-engineering," in Metz, Davidson, Swart, and Pan, note 13 above, pages 301–43.

22. Pacala and Socolow, note 2 above.

23. World Resources Institute, *Building a Safe Climate* (Washington, DC: World Resources Institute, 1988).

24. Pacala and Socolow, note 2 above.

25. Pacala and Socolow, note 2 above.

26. Pacala and Socolow, note 2 above.

27. G. Muttitt and B. Diss, "Carbon Injection: An Addict's Response to Climate Change," *The Ecologist*, 22 October 2001.

USEFUL ONLINE REFERENCES

BP Statistical Review of World Energy, by British Petroleum; http://www.bp.com/subsection.do?categoryId=95&contentId=2006480

International Energy Annual 2002, by the Energy Information Administration; http://www.eia.doe.gov/emeu/iea/contents.html

International Energy Outlook, 2003, by the Energy Information Agency; http://www.eia.doe.gov/oiaf/ieo/index.html

Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1-4 October, 2002, Kyoto, Japan, edited by John Gale and Yoichi Kaya; http://www.ieagreen.org.uk/ghgt6.htm

World Energy Outlook 2002, by the International Energy Agency; http://library.iea.org/dbtw-wpd/Textbase/nppdf/stud/02/weo2002_1.pdf (by subscription)

Key World Energy Statistics, by the International Energy Agency; http://www.iea.org/dbtw-wpd/bookshop/add.aspx?id=144

Land Use, Land Use Change and Forestry, edited by Robert T. Watson et al.; http://www.grida.no/climate/ipcc/land_use/index.htm

IPCC Third Assessment Report: Climate Change 2001, by the Intergovernmental Panel on Climate Change; http://www.ipcc.ch/index.html

Special Report on Emissions Scenarios, by the Intergovernmental Panel on Climate Change; http://www.grida.no/climate/ipcc/emission/index.htm

The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, by the Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council; http://www.nap.edu/books/0309091632/html/