



SLEIPNER
NATURAL
GAS RIG

NORTH SEA

Capturing Greenhouse Gases

by Howard Herzog, Baldur Eliasson and Olav Kaarstad

UTSIRA FORMATION

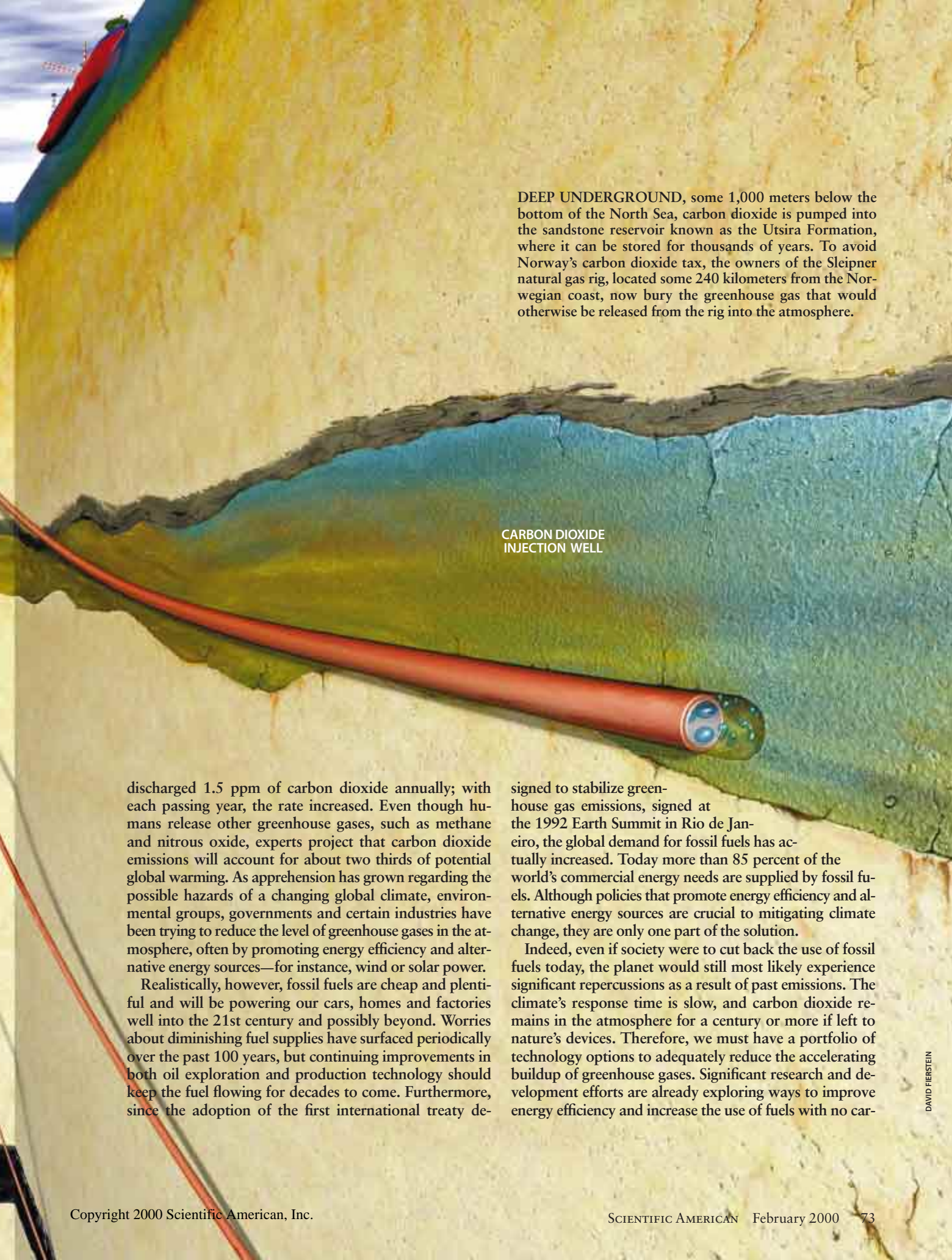
*Sequestering carbon dioxide underground
or in the deep ocean could help alleviate
concerns about climate change*

The debate over climate change has shifted. Until very recently, scientists still deliberated whether human activity was altering the global climate. Specifically, was the release of greenhouse gases, which trap heat radiating from the earth's surface, to blame? With scientific evidence mounting in favor of the affirmative, the discussion is now turning to what steps society can take to protect our climate.

One solution almost certainly will not succeed: running out of fossil fuels—namely, coal, oil and natural gas. Morris Adelman, professor emeritus at the Massachusetts Institute of Technology and expert on the economics of oil and gas, has consistently made this point for 30 years. In the past century and a half, since the beginning of the industrial age, the concentration of carbon dioxide in the atmosphere has risen by almost one third, from 280 to 370 parts per million (ppm)—primarily as a result of burning fossil fuels. In the 1990s, on average, humans

NATURAL GAS
PIPELINES

NATURAL GAS



DEEP UNDERGROUND, some 1,000 meters below the bottom of the North Sea, carbon dioxide is pumped into the sandstone reservoir known as the Utsira Formation, where it can be stored for thousands of years. To avoid Norway's carbon dioxide tax, the owners of the Sleipner natural gas rig, located some 240 kilometers from the Norwegian coast, now bury the greenhouse gas that would otherwise be released from the rig into the atmosphere.

CARBON DIOXIDE
INJECTION WELL

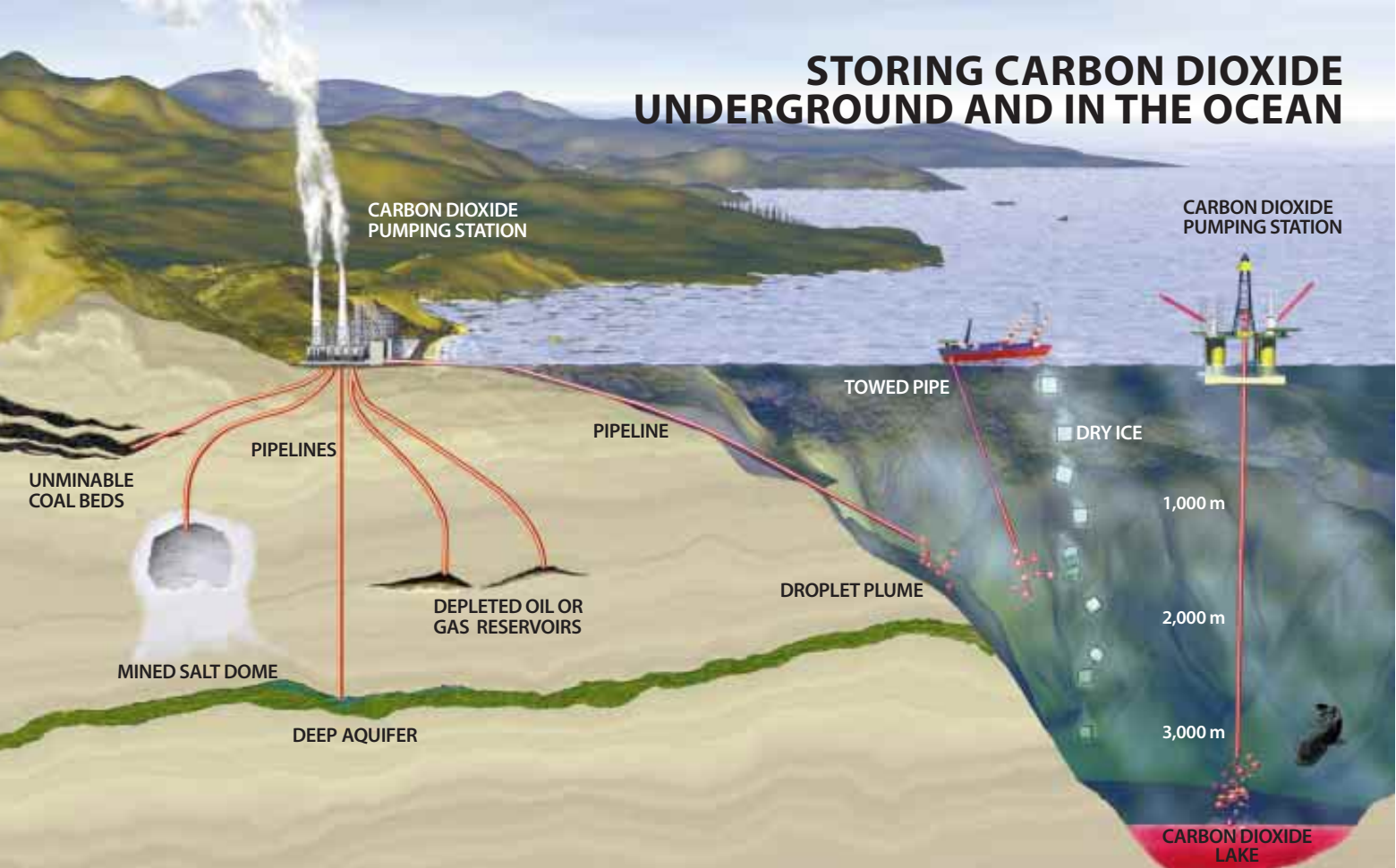
discharged 1.5 ppm of carbon dioxide annually; with each passing year, the rate increased. Even though humans release other greenhouse gases, such as methane and nitrous oxide, experts project that carbon dioxide emissions will account for about two thirds of potential global warming. As apprehension has grown regarding the possible hazards of a changing global climate, environmental groups, governments and certain industries have been trying to reduce the level of greenhouse gases in the atmosphere, often by promoting energy efficiency and alternative energy sources—for instance, wind or solar power.

Realistically, however, fossil fuels are cheap and plentiful and will be powering our cars, homes and factories well into the 21st century and possibly beyond. Worries about diminishing fuel supplies have surfaced periodically over the past 100 years, but continuing improvements in both oil exploration and production technology should keep the fuel flowing for decades to come. Furthermore, since the adoption of the first international treaty de-

signed to stabilize greenhouse gas emissions, signed at the 1992 Earth Summit in Rio de Janeiro, the global demand for fossil fuels has actually increased. Today more than 85 percent of the world's commercial energy needs are supplied by fossil fuels. Although policies that promote energy efficiency and alternative energy sources are crucial to mitigating climate change, they are only one part of the solution.

Indeed, even if society were to cut back the use of fossil fuels today, the planet would still most likely experience significant repercussions as a result of past emissions. The climate's response time is slow, and carbon dioxide remains in the atmosphere for a century or more if left to nature's devices. Therefore, we must have a portfolio of technology options to adequately reduce the accelerating buildup of greenhouse gases. Significant research and development efforts are already exploring ways to improve energy efficiency and increase the use of fuels with no car-

STORING CARBON DIOXIDE UNDERGROUND AND IN THE OCEAN



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES	STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology	Droplet Plume	Minimal environmental effects	Some leakage
Mined Salt Domes	Custom designs	High costs	Towed Pipe	Minimal environmental effects	Some leakage
Deep Saline Aquifers	Large capacity	Unknown storage integrity	Dry Ice	Simple technology	High costs
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity	Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

STORAGE SITES for carbon dioxide in the ground and deep sea should help keep the greenhouse gas out of the atmosphere where it

now contributes to climate change. The various options must be scrutinized for cost, safety and potential environmental effects.

bon content (renewable energy sources or nuclear power). But a third approach is attracting notice as people recognize that the first two options will simply not be sufficient: carbon sequestration, the idea of finding reservoirs where carbon dioxide can be stored rather than allowing it to build up in the atmosphere.

Our strategy may surprise some readers. Sequestering carbon is often connected to planting trees: trees (and vegetation in general) absorb carbon dioxide from the air as they grow and hold on to that carbon for their lifetime [see box on page 77]. Scientists estimate that, all together, plants currently retain about 600 gigatons of carbon, with another 1,600 gigatons in the soil.

Plants and soils could perhaps sequester another 100 gigatons or more of carbon, but additional sinks will be needed to meet the challenge of escalating greenhouse gas emissions. So during

the past 10 years, the three of us have explored another possibility: capturing carbon dioxide from stationary sources—for example, a chemical factory or an electric power plant—and injecting it into the ocean or underground. We are not alone in our efforts but are part of a worldwide research community that includes the International Energy Agency (IEA) Greenhouse Gas Research and Development Program, as well as government and industry programs.

A New Approach in Norway

Sleipner offshore oil and natural gas field is in the middle of the North Sea, some 240 kilometers off the coast of Norway. Workers on one of the natural gas rigs there inject 20,000 tons of carbon dioxide each week into the pores of a sandstone layer 1,000 meters below the seabed. When the injection at Sleip-

ner began in October 1996, it marked the first instance of carbon dioxide being stored in a geologic formation because of climate considerations.

How did this venture come about? One reservoir at Sleipner contains natural gas diluted with 9 percent carbon dioxide—too much for it to be attractive to customers, who generally accept no more than 2.5 percent. So, as is common practice at other natural gas fields around the world, an on-site chemical plant extracted the excess carbon dioxide. At any other installation, this carbon dioxide would simply be released to the atmosphere. But the owners of the Sleipner field—Statoil (where one of us, Kaarstad, works as a researcher), Exxon, Norsk Hydro and Elf—decided to sequester the greenhouse gas by first compressing it and then pumping it down a well into a 200-meter-thick sandstone layer, known as the Utsira Formation,

DAVID FIERSTEIN

which was originally filled with saltwater. The nearly one million tons of carbon dioxide sequestered at Sleipner last year may not seem large, but in the small country of Norway, it amounts to about 3 percent of total emissions to the atmosphere of this greenhouse gas.

The principal motivation for returning carbon to the ground at Sleipner was the Norwegian offshore carbon dioxide tax, which in 1996 amounted to \$50 for every ton of the gas emitted (as of January 1, 2000, the tax was lowered to \$38 per ton). The investment in the compression equipment and carbon dioxide well totaled around \$80 million. In comparison, if the carbon dioxide had been emitted to the atmosphere, the companies would have owed about \$50 million each year between 1996 and 1999. Thus, the savings paid off the investment in only a year and a half.

In other parts of the world, companies are planning similar projects. In the South China Sea, the Natuna field contains natural gas with nearly 71 percent carbon dioxide. Once this field has been developed commercially, the excess carbon dioxide will be sequestered. Other studies are investigating the possibility of storing captured carbon dioxide underground, including within liquefied natural gas installations at the Gorgon field on Australia's Northwest Shelf and the Snøhvit ("Snow White") gas field in the Barents Sea off northern Norway, as well as the oil fields of Alaska's North Slope.

In all the projects now under way or in development, carbon dioxide must be captured for commercial reasons—for instance, to purify natural gas before it can be sold. The choice facing the companies involved is therefore between releasing the greenhouse gas to the atmosphere or storing it. They are not deciding whether to collect the carbon dioxide in the first place. We expect that more such companies needing to reduce carbon dioxide emissions will opt for sequestration in the future, but convincing other businesses to capture carbon dioxide emissions from large point sources such as electric power plants is more difficult because of the costs associated with carbon dioxide collection.

Underground or Underwater

The technology for pumping carbon dioxide into the ground is actually well established—it is essentially the reverse of pumping oil and natural gas out of the ground. In fact, the practice

is common at many oil fields today. Injecting carbon dioxide into an existing oil reservoir increases the mobility of the oil inside and thereby enhances the well's productivity. During 1998, U.S. oil field workers pumped a total of about 43 million tons of carbon dioxide into the ground at more than 65 enhanced oil recovery (EOR) projects. Yet this quantity adds up to comparatively little carbon sequestration. In contrast, geologic formations, including saline aquifer formations (such as that at Sleipner), unminable coal beds, depleted oil or gas reservoirs, rock caverns and mined salt domes all around the world, can collectively hold hundreds if not thousands of gigatons of carbon.

Although geologic formations show great promise as storage sites, the largest potential reservoir for anthropogenic car-

bon dioxide is the deep ocean. Dissolved in its waters, the ocean holds an estimated 40,000 gigatons of carbon (compared with 750 gigatons in the atmosphere), but its capacity is much larger. Even if humans were to add to the ocean an amount of carbon dioxide equivalent to doubling the preindustrial atmospheric concentration of the gas, it would change the carbon content of the deep ocean by less than 2 percent. Indeed, slow-acting, natural processes will direct about 85 percent of present-day emissions into the oceans over hundreds of years. Our idea is to accelerate these events.

For ocean sequestration to be effective, the carbon dioxide must be injected into the sea below the thermocline—the layer of ocean between approximately 100 and 1,000 meters, in which water temperatures decrease dramatically with

THE BASICS

BURYING CARBON DIOXIDE

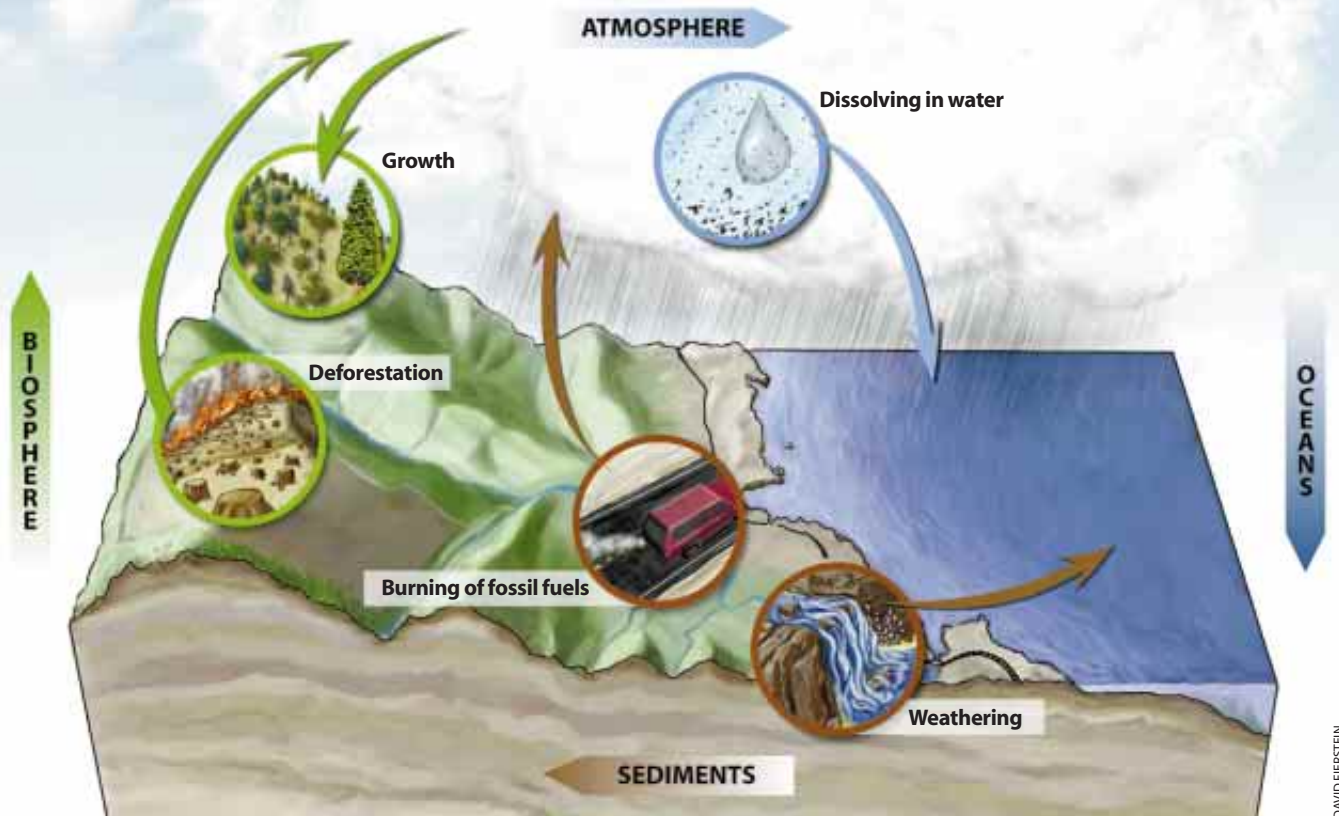
THE AUTHORS REVIEW CARBON SEQUESTRATION TECHNOLOGY

What is carbon sequestration? The idea is to store the greenhouse gas carbon dioxide in natural reservoirs rather than allowing it to build up in the atmosphere. Although sequestering carbon is often connected to planting trees, we are investigating the possibility of capturing carbon dioxide from stationary sources—an electric power plant, for example—and injecting it into the ocean or underground.

Where exactly will the carbon dioxide be stored? It can be pumped into underground geologic formations, such as unminable coal beds, depleted oil or gas wells, or saline aquifers, in a process that is essentially the reverse of pumping oil up from below the earth's surface. Engineers are also looking into the possibility of bubbling carbon dioxide directly into the ocean at concentrations that will not affect the surrounding ecosystem and at depths that will ensure it remains in the ocean.

How will scientists make certain it is stored safely? Making sure carbon dioxide will be stored in a safe and environmentally sound manner is one of our primary goals. Memories of the 1986 Lake Nyos tragedy in Cameroon (in which a huge bubble of carbon dioxide erupted from the lake, suffocating some 1,700 people), raise the issue of safety, particularly for underwater storage. Yet the situation in the lake was entirely different than the scenario we envision for carbon sequestration in the ocean. A small lake simply cannot hold a large amount of carbon dioxide, so the Nyos eruption was inevitable. There are no such limitations in the oceans. In the case of underground storage, nature has demonstrated a safe track record: reservoirs such as the McElmo Dome in southwestern Colorado have held large quantities of carbon dioxide for centuries.

Are there any active carbon sequestration projects today? The Sleipner natural gas rig off the coast of Norway currently pumps carbon dioxide into a saline aquifer 1,000 meters below the seafloor. Although Sleipner is the only sequestration project driven solely by climatic change considerations, other commercial projects demonstrate the technology. More than a dozen power plants capture carbon dioxide from their flue gas, including the Shady Point, Okla., plant built by the international engineering company ABB. And at over 65 oil wells in the U.S., companies inject the gas underground to enhance the efficiency of oil drilling.



NATURAL STORES OF CARBON exist in the atmosphere, oceans, sediments and biosphere; exchange between these reservoirs occurs in a variety of ways. When humans burn fossil fuels, we transfer carbon originally stored in the deep sediments into the atmosphere. The goal of carbon sequestration is to redirect carbon from the atmosphere into one of the other three reservoirs.

depth. The cooler, denser water below travels extremely slowly up through the thermocline. Therefore, the water beneath the thermocline may take centuries to mix with the surface waters, and any carbon dioxide below this boundary will be effectively trapped. In general, the deeper we inject the carbon dioxide, the longer it will take to reach the atmosphere.

Carbon dioxide can be introduced into seawater in two ways: dissolving it at moderate depths (from 1,000 to 2,000 meters) to form a dilute solution or injecting it below 3,000 meters to create what we call a carbon dioxide lake. The first strategy seeks to minimize local environmental effects by diluting the carbon dioxide, whereas the lake approach tries to maximize the length of time the carbon dioxide will reside in the ocean.

The concept of storing carbon dioxide in the ocean can be traced to a 1977 paper by Cesare Marchetti of the International Institute for Applied Systems Analysis in Laxenburg, Austria, who suggested that carbon dioxide could be piped into the waters of the Mediterranean Sea at Gibraltar, where it would naturally flow out into the Atlantic and be carried to the deep ocean. Even today building a pipe along the ocean floor to

transport carbon dioxide to an appropriate depth remains one of the more realistic options for carbon sequestration. Other injection scenarios that have been suggested include dropping dry ice into the ocean from ships, introducing carbon dioxide at 1,000 meters through a pipe towed by a moving ship, and running a pipe down 3,000 meters or more to depressions in the seafloor.

Safe and Sound?

Despite the availability of the technology necessary to proceed with carbon storage in both terrestrial and oceanic reservoirs, we need to understand better what the consequences for the environment will be. Obviously, the process of storing carbon dioxide needs to be less damaging to the environment than the continued release of the greenhouse gas. In the case of underground storage, we must be sure to assess the long-term stability of any formation under consideration as a reservoir. The structural integrity of a site is important not only to ensure that the gas does not return to the atmosphere gradually but also because a sudden release of the carbon dioxide in a populated area could be catastrophic. Carbon dioxide is heavier

than air, and a rapid, massive discharge of the gas would displace oxygen at the surface, suffocating people and wildlife. Fortunately, though, nature has stored carbon dioxide underground for millions of years in reservoirs such as McElmo Dome in southwestern Colorado, so we know there are ways to do it safely.

Ocean sequestration presents a different set of challenges. The leading concern is the repercussion it will have on the acidity of the ocean. Depending on the method of carbon dioxide release, the pH of seawater in the vicinity of an injection site could be between 5 and 7. (A pH of 7 is considered neutral; the pH of seawater is normally around 8.)

A large change in acidity could be harmful to organisms such as zooplankton, bacteria and bottom-dwelling creatures that cannot swim to less acidic waters. Research by one of us (Herzog) and M.I.T. colleague E. Eric Adams, however, suggests that keeping the concentration of carbon dioxide dilute could minimize or even eliminate problems with acidity. For example, a dilution factor of one part per million yields a change in pH of less than 0.1. This reduced concentration could easily be achieved by releasing the carbon dioxide as small droplets from a pipe on the seafloor or on a moving ship.

Over the next several years, the scientific community will be conducting a number of experiments to assess how large amounts of carbon dioxide can be stored in a safe and environmentally sound manner. In the summer of 2001, for instance, a team of researchers from the U.S., Japan, Switzerland, Norway, Canada and Australia will begin a study off the Kona Coast of Hawaii to examine the technical feasibility and environmental effects of carbon storage in the ocean. (Two of us are participating in this project, Herzog as a member of the technical committee and Eliasson as a member of the steering committee.)

Our plan is to run a series of about 10 tests over a period of two weeks, involving the release of carbon dioxide at a depth of 800 meters. We will be monitoring the resulting plume and taking measurements, including the pH of the water and the amount of dissolved inorganic carbon. These data will allow us to refine computer models and thereby generalize the results of this experiment to predict environmental responses more accurately. We are also interested in what technical design works best to rapidly dilute the small droplets of carbon dioxide.

Money Matters

Along with questions of environmental safety and practicality, we must look at how much carbon sequestration will cost. Because electricity-generating power plants account for about one third of all carbon dioxide released to the atmosphere worldwide and because such plants are large, concentrated sources of emissions, they provide a logical target for implementing carbon sequestration. Furthermore, such plants have had experience reducing pollutants in the past. (Notably, though, attention has primarily focused on controlling such contaminants as particulate matter, sulfur oxides, nitrogen oxides or even carbon monoxide—but not on carbon dioxide itself.)

Devices known as electrostatic precipitators, first introduced in the 1910s, helped to clean up the particles emitted from burning fossil fuels while raising the price of electricity only modestly. Today a modern power plant that includes state-of-the-art environmental cleanup equipment for particulates, sulfur oxides and nitrogen oxides costs up to 30 percent more to install than a plant without such equipment. This environmental equipment adds only between 0.1 and 0.5 of a cent per kilowatt-hour

to the price of the electricity generated.

Because the exhaust gases of fossil-fueled power plants contain low concentrations of carbon dioxide (typically ranging from 3 to 15 percent), it would not be economical to funnel the entire exhaust stream into storage sites. The first step, therefore, should be to concentrate the carbon dioxide found in emissions. Unfortunately, with existing equipment this step turns out to be the most expensive. Thus, developing technology that lowers these costs is a major goal.

The most common method for separating carbon dioxide involves mixing a solution of dilute monoethanolamine (MEA) with the flue gases inside the absorption tower of a plant designed to capture the greenhouse gas. The carbon

dioxide in the exhaust reacts with the MEA solution at room temperature to form a new, loosely bound compound. This compound is then heated in a second column, the stripping tower, to approximately 120 degrees C to release the carbon dioxide. The gaseous carbon dioxide product is then compressed, dried, chilled, liquefied and purified (if necessary); the liquid MEA solution is recycled. Currently this technology works well, but it must become more energy-efficient if it is to be applied to large-scale carbon sequestration. Today only a handful of power plants, including one built in Shady Point, Okla., by ABB (where Eliasson serves as head of global change research), capture carbon dioxide from their flue gases. The carbon dioxide

PLANT A TREE

ANOTHER OPTION FOR STORING CARBON NEEDS ONLY SUN AND WATER

For over a decade, an organized carbon sequestration project has been under way in the deforested regions and farmlands of Guatemala. No underground pipes or pumping stations are required—just trees. As the plants grow, they absorb carbon dioxide from the atmosphere, which they store as carbon in the form of wood. Hoping to capitalize on this natural vehicle for sequestering carbon, companies and governments have initiated reforestation, afforestation (planting trees on land not previously forested) and agroforestry (integrating trees with agricultural crops) efforts as a way to meet obligations set forth in the Kyoto Protocol, the international environmental treaty on lowering greenhouse gas emissions.

In 1988 AES, a U.S.-based electrical company, pioneered the first forestry project designed to offset carbon dioxide emissions. At the time, AES was about to build a new coal-fired power plant in Connecticut, which was expected to release 52 million tons of carbon dioxide during its 40-year life span. Working in Guatemala with the World Resources Institute (WRI) and the relief organization CARE, AES created community woodlots, introduced agroforestry practices and trained forest-fire brigades. According to WRI calculations, up to 58 million tons of carbon dioxide will be absorbed over the lifetime of the project. Currently more than a dozen such programs

are under way on some four million hectares of forest land, including areas in the U.S., Norway, Brazil, Malaysia, Russia and Australia.

According to recent estimates, forests around the globe today store nearly one trillion tons of carbon. Scientists calculate that to balance current carbon dioxide emissions, people would have to plant new forests every year covering an area of land equivalent to the whole of India. Forestry projects are not a quick-fix solution, but they do offer many benefits, ranging from better habitats for wildlife to increased employment. Nevertheless, the potential for trees to serve as a reservoir for carbon is limited, and the approach has its drawbacks. Tree plantations drain native plant biodiversity and can disturb local communities, forcing them to relocate. As with many proposed solutions to climate change, trees will be effective only as one part of a global commitment to reduce greenhouse gas emissions. —Diane Martindale



SEEDLINGS are planted by workers in Fiji as part of a reforestation effort.

PETER ARNOLD, INC.

A BREAKTHROUGH IN CLIMATE CHANGE POLICY?

BY DAVID W. KEITH AND EDWARD A. PARSON

As a result of human activities, the atmospheric concentration of carbon dioxide has increased by 31 percent over the past two centuries. According to business-as-usual projections, it will reach twice the preindustrial level before 2100. Although there is little doubt that this increase will noticeably transform the climate, substantial uncertainties remain about the magnitude, timing and regional patterns of climate change; even less is known about the ecological, economic and social consequences.

Despite these uncertainties, an international consensus has emerged regarding the importance of preventing runaway levels of carbon dioxide in the atmosphere. An effort to stabilize the concentration of carbon dioxide at even double its preindustrial level—generally considered the lowest plausible target—will require reducing global carbon dioxide emissions by about 50 percent from projected levels by 2050. Not surprisingly, such an extreme reduction will require a fundamental reorganization of global energy systems.

Most current assessments of greenhouse gas emissions assume that the reductions will be achieved through a mix of increasing energy efficiency and switching to nonfossil-fuel alternative energy sources, such as solar, wind, biomass or nuclear. In the accompanying article, "Capturing Greenhouse Gases," the authors review a radically different approach: burning fossil fuels without releasing carbon dioxide to the atmosphere by separating the carbon emissions and burying them underground or in the deep ocean. We believe this approach—termed carbon management—has fundamental implications for the economics and politics of climate change.

Stabilizing the carbon dioxide concentration at 550 parts per million (ppm)—double the preindustrial level—is widely considered an ambitious target for emissions control. Yet this concentration will still cause substantial climate change. The resulting environmental problems, however, will most likely have only a small effect on the world's overall economic output; rich countries in particular should emerge relatively unscathed. But the results for specific regions will be more pronounced, with some places benefiting and others suffering. For instance, although parts of the northern U.S. may enjoy warmer winters, entire ecosys-

tems, such as the southwestern mountain forests, alpine meadows and certain coastal forests, may disappear from the continental U.S. These likely consequences—and more important, the possibility of unanticipated changes—are compelling reasons to try to stabilize concentrations below 550 ppm, if it can be done at an acceptable cost.

At present, the cost of holding concentrations to even 550 ppm through conventional means appears high, both in dollars and in other environmental problems. All nonfossil-fuel energy sources available today are expensive, and renewable sources have low power densities: they produce relatively little power for the amount of land required. Large-scale use of renewable energy could thereby harm our most precious environmental resource: land. Although technological advances should reduce the cost of renewables, little can be done to improve their power densities, which are intrinsic to the sources.

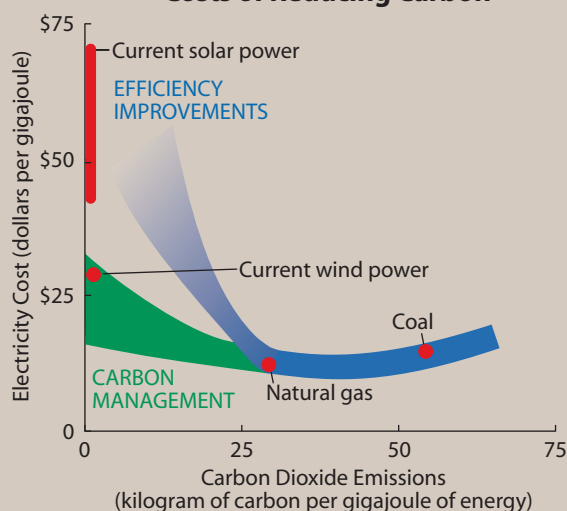
So must we conclude that reducing carbon emissions without causing other unacceptable environmental impacts will deliver a massive economic blow? Not necessarily. The crux of the cost problem is predicting how fast money-saving technical advances might develop in response to a carbon tax or some other form of regulation. Notably, most economic models used today to assess the cost of reducing emis-

sions assume that innovation proceeds at its own pace and cannot be accelerated by policy. Under this assumption, delaying efforts to cut emissions makes sense because it will allow time to develop better technology that will lower the cost of reductions. Under the contrary assumption—which we regard as closer to the truth—innovation responds strongly to price and policy signals. In this case, early policy action on climate change is advantageous, because it would stimulate the innovations that reduce the cost of making large emission reductions.

Carbon management may be just such an innovation. Certain carbon management

technologies are already available and appear to be significantly cheaper than renewables for generating electricity. To achieve deep reductions in greenhouse gas emissions, however, society must also start using carbon-free fuels, such as hydrogen, for transportation. Here the relative advantage of carbon management over renewables is even greater than in producing electricity. Furthermore, these technologies offer one significant advantage over alternative energy sources: because they are more compatible with the existing energy

Costs of Reducing Carbon



REDUCING CARBON DIOXIDE EMISSIONS by switching from coal to natural gas can save money. The authors argue that further reductions will be cheaper to make by carbon management (green) than by solar power or by extreme efficiency improvements (blue). Although wind power is relatively cheap, the land area required may preclude its widespread use.

infrastructure, we expect their costs to fall more quickly than those of renewables.

Carbon management weakens the link between burning fossil fuels and releasing greenhouse gases, making the world's economic dependence on fossil fuels more sustainable. This gives carbon management a crucial advantage: by reducing the threat to fossil-fuel industries and fossil-fuel-rich nations, carbon management may ease current political deadlocks. Stated bluntly, if society adopts carbon management widely, existing fossil-fuel-dependent industries and nations may continue to operate profitably both in present energy markets and in new

markets that develop around carbon management, making them more willing to tolerate policies that pursue substantial reduction of atmospheric emissions.

Environmentalists, however, are likely to find carbon management profoundly divisive for several reasons. Carbon sequestration is only as good as the reservoirs in which the carbon is stored. The unfortunate history of toxic and nuclear waste disposal has left many reasonable people skeptical of expert claims about the longevity of underground carbon disposal. As researchers assess the safety of proposed carbon reservoirs both underground and in the ocean, they must address such skepticism evenhandedly.

Perhaps even more disconcerting for environmentalists, though, is that carbon management collides with a deeply rooted belief that continued dependence on fossil fuels is an intrinsic problem, for which the only acceptable solution is renewable energy. Carbon management was first proposed as “geoengineering,” a label it now shares with proposals to engineer the global climate, for example, by injecting aerosols into the stratosphere to reflect solar radiation and cool the earth’s surface. Many environmentalists hold a reasonable distaste for large-scale technical fixes, arguing that it would be better to use energy sources that do not require such massive clean-up efforts.

Carbon management is a promising technology, but it remains unproved. And caution is certainly wise: the history of energy technologies is littered with options once touted as saviors that now play at most minor roles (for example, nuclear energy). Exploring the potential of either carbon management or renewable energy will require political and economic action now—that is, greater support for basic energy research and carbon taxes or equivalent policy measures that give firms incentives to develop and commercialize innovations that reduce emissions at a reasonable cost. It may be that carbon management will allow the world—at long last—to make deep cuts in carbon dioxide emissions at a politically acceptable cost. Indeed, for the next several decades, carbon management may be our best shot at protecting the global climate.

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ciate professor at the John F. Kennedy School of
Government at Harvard University.*

is then sold for commercial applica-
tions, such as freeze-drying chicken or
carbonating beer and soda.

Another application for captured car-
bon dioxide offers a number of possible
benefits. Methanol can be used as fuel
even now. Generating this cleaner source
of energy from captured carbon dioxide
and hydrogen extracted from carbon-
free sources would be more expensive
than producing methanol from natural
gas, as is currently done. But by reusing
carbon dioxide—and by giving it a mar-
ket value—this procedure ought to re-
duce overall emissions, provide an in-
centive to lower the costs of carbon
dioxide-capture technology and help
start a transition to more routine use of
cleaner fuels.

Scientists, policymakers and the public
must deal with the continuing impor-
tance of coal, oil and natural gas as a
source of energy, even in a world con-
strained by concerns about climate
change. The basic technology needed to
use these fuels in a climate-friendly man-
ner does exist. Current equipment for
capturing carbon dioxide from power
plants would raise the cost of generating
electricity by 50 to 100 percent. But be-
cause sequestration does not affect the
cost of electricity transmission and distri-
bution (a significant portion of con-
sumers’ electricity bills), delivered prices
will rise less, by about 30 to 50 percent.
Research into better separation tech-
nologies should lead to lowered costs.

What needs to happen for carbon se-
questration to become common prac-



CAPTURE PLANT located in Shady Point, Okla., separates carbon dioxide from its exhaust fumes; the gas is then sold for use in the food industry.

tice? First, researchers need to verify the feasibility of the various proposed storage sites, in an open and publicly acceptable process. Second, we need leadership from industry and government to demonstrate these technologies on a large enough scale. Finally, we need improved technology to reduce costs associated with carbon dioxide separation from power plants. The Sleipner project has shown that carbon sequestration represents a realistic option to reduce carbon dioxide emissions when an economic incentive exists. During the past 100 years, our energy supply system has undergone revolutionary changes—from a stationary economy based on coal and steam to a mobile economy based on liquid fuels, gas and electricity. The changes over the next 100 years promise to be no less revolutionary. SA

The Authors

HOWARD HERZOG, BALDUR ELIASSON and OLAV KAARSTAD met in Amsterdam in March 1992 at the First International Conference on Carbon Dioxide Removal. Herzog, a principal research engineer at the Massachusetts Institute of Technology Energy Laboratory, is the primary author of a 1997 U.S. Department of Energy White Paper on carbon sequestration. Eliasson, head of ABB’s Energy and Global Change Program, is the Swiss representative to as well as vice chairman of the International Energy Agency’s Greenhouse Gas Research and Development Program. Kaarstad, principal research adviser in the area of energy and environment at the Norwegian oil and gas company Statoil, is currently involved in the ongoing carbon dioxide-injection project at the Sleipner field in the North Sea.

Further Information

ABB Group’s Energy and Global Change Web site is at www.abb.com/ (click on “Environment,” then on “Energy and Global Change”).
IEA Greenhouse Gas Research and Development Program Web site is at www.ieagreen.org.uk/
M.I.T. Energy Laboratory Web site is at web.mit.edu/energylab/www
Statoil Web site is at www.statoil.com (for information on the Sleipner area in particular, go to www.statoil.com/statoilcom/svg00990.nsf/ealias/Sleipner).
U.S. Department of Energy’s Office of Fossil Energy Web site is at www.fe.doe.gov/coal_power/sequestration/
U.S. Department of Energy’s Office of Science Web site is at www.sc.doe.gov/production/ober/carbseq.html