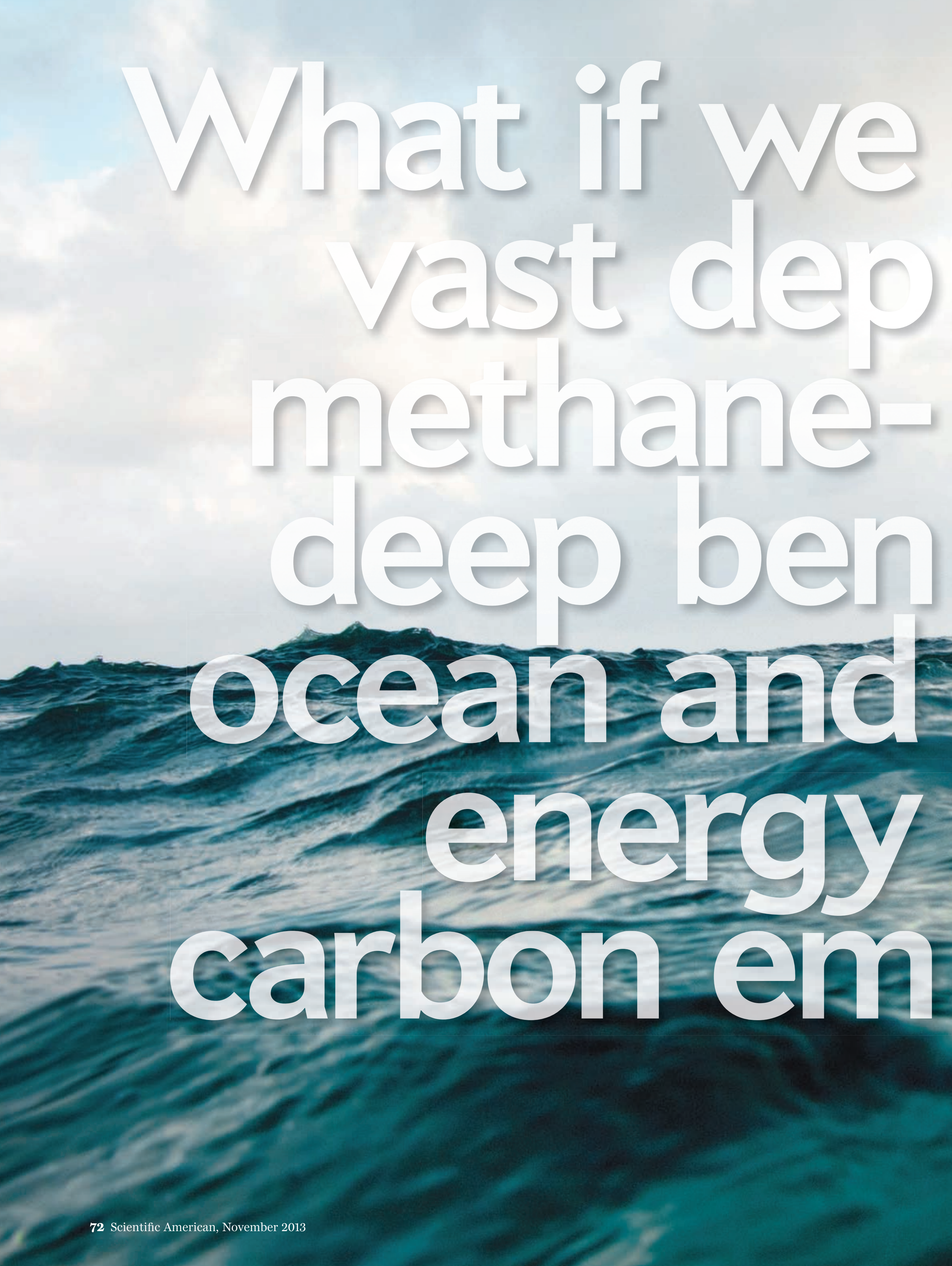

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CLIMATE

The One-Stop Carbon Solution

By Steven L. Bryant

IN BRIEF

Most countries are not capturing carbon dioxide emissions and storing them underground, because the process is expensive.

A closed-loop system that injects CO_2 into hot brine brought to the surface from deep underground could make CO_2 storage economical by providing geothermal energy and methane for fuel. The CO_2-laden brine would be sent back down for permanent storage.

Calculations show that enough deep brine exists along the U.S. Gulf Coast to store one sixth of the country's CO_2 emissions and to meet one sixth of its demand for natural gas annually.

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MARK TWAIN, IT IS CLAIMED, OBSERVED THAT EVERYBODY COMPLAINS ABOUT THE WEATHER, but nobody does anything about it. A modern-day Twain might remark that everybody talks about climate change, but nobody is taking serious action. One big reason is economics. Reducing the buildup of carbon dioxide in the atmosphere—the major human-based driver of climate change—requires an expensive shift away from coal and oil as our prime sources of energy. Or it requires costly technology to capture CO_2 as industry emits it and then store the gas where it will stay put for centuries to come.

Yet what if a technology could economically do both: produce large amounts of energy and significantly reduce greenhouse gas emissions? And what if that technology fit seamlessly into the country's existing industrial infrastructure? This scenario could become reality along the U.S. Gulf Coast. Because of a special geologic situation there, a huge amount of CO_2 could be stored several kilometers underground in hot, salty fluid called brine, and the storage procedure itself would produce a vast amount of methane for fuel, as well as usable heat. Neither the storage nor the production of methane or of geothermal energy is economical on its own. Yet new calculations show that when the processes are combined in a closed-loop system, they could pay off handsomely in the U.S. and elsewhere.

GRAVITY RULES

WAIT, METHANE? The latest villain of climate change? The gas that can escape from pipelines and from gas wells in hydraulically fractured shale and that, molecule for molecule, has 20 times the global-warming power of CO_2? Yes.

To understand the logic, first take a look at capturing and burying carbon, known as sequestration. Thinking about the challenges is what led my colleagues and me to propose a seemingly heretical system.

The goal of carbon capture and storage is to grab CO_2 molecules at the source–the flue gas that rises from a fossil-fuel power plant—and lock them away so they do not enter the atmosphere. "Storage" sounds straightforward, but the only repository anywhere near big enough to house the incredible volume of CO_2 is underground. Scientists have determined that the pores of sedimentary rock in the top few kilometers of the earth's crust could theoretically hold centuries' worth of CO_2 emissions.

To meet a target of storing, say, 15 percent of U.S. emissions, up to a gigaton of CO_2 would have to be sequestered a year. The global energy industry produces about four gigatons of crude oil and two gigatons of natural gas from sedimentary rocks every year. The scale of this activity indicates that moving a gigaton of compressed CO_2 into the earth's crust should be achievable, although the effort would be enormous. Of course, other changes at a comparable scale, such as improving energy efficiency and switching to nonfossil fuels, would reduce the CO_2 created in the first place.

The next step seems obvious: start adapting proved oil and gas production technologies to implement this form of geologic carbon storage—and start now. Unfortunately, this strategy faces a fundamental disadvantage. Over time the CO_2 would tend to rise back toward the surface through fissures and pores, eventually escaping from the ground into the atmosphere unless it encountered a "seal"—a layer of rock with pores so tiny that the gas could not push through it.

Our petroleum industries rely on such natural upward flows. The oil and gas in underground reservoirs arrived there from even deeper rocks along various conduits. In this long, slow, upward cascade, some fluid gets trapped, but much of it keeps migrating until it reaches the surface. Most prospectors, during the early oil industry, drilled where they spotted surface seeps.

Widespread study of underground CO_2 plumes by various scientists shows a similar situation: many geologic structures will stop CO_2 from rising, but conduits will also permit upward movement. Yet engineers could exploit an interesting quirk of CO_2. Most liquids become less dense when gas dissolves into them. But when CO_2 dissolves into water, the liquid becomes denser. Most watery liquid that is deep underground is brine, and when CO_2 dissolves into the salty fluid the brine also becomes denser. The buoyancy problem disappears; CO_2 stored in this form would tend to sink, moving away from the earth's surface and thereby enhancing storage security.

ENERGY COVERS THE COST

THE CATCH is that CO_2 takes a long time to dissolve on its own into deep brine at the typical temperatures and pressures where it exists. So Mac Burton, then my graduate student, and I considered a radical idea: drill a well down into the brine, bring it up to the surface, pressurize it, inject CO_2 (which dissolves quickly in a mixing tank) and send the brine back down underground.

Obviously, this plan would require a lot of energy. And brine can hold relatively little CO_2 by weight, so large quantities would have to be moved. Either challenge could be a deal breaker.

The solution to the second challenge did not seem excessively daunting. Oil companies, for example, commonly drill wells in an evenly spaced pattern across a reservoir. Water or brine is injected down a subset of the wells to push underground oil through

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the reservoir and up through the other wells in the pattern. Currently the industry injects about 10 gigatons of brine into reservoirs a year—most of it tapped from the reservoirs themselves. Thus, achieving the brine-flow rates needed for meaningful CO_2 storage is feasible. One subset of wells at a storage site would extract brine from a reservoir; another subset would simultaneously inject brine containing dissolved CO_2.

The other challenge—the capital needed to drill all those wells and the energy needed to run them—was much harder to justify. Industry has not been rushing to capture and store CO_2, because emitters pay no penalty or price for sending CO_2 into the atmosphere. Industry has no economic reason to sequester the emissions. Policy arguments for protecting the planet or for covering the "full cost" of fossil-fuel use, which includes altering the environment, have not persuaded anyone to impose a price. At first glance, we saw no way to pay for injecting CO_2 into brine.

Not long ago, however, an idea emerged in an office down the hall from mine at the University of Texas at Austin that promised to resolve the dilemma. Gary Pope—a fellow petroleum engineering professor who has devoted most of his career to developing better ways to push oil out of reservoirs—realized that a hidden resource could be exploited.

The Gulf of Mexico, along with every other oil-producing region in the world, has deep, saline aquifers that are rich in dissolved methane. Methane is the main component of natural gas, so it can be burned in local power plants or readily distributed nationwide through the U.S.'s extensive network of gas pipelines. As the brine reached the surface, we could pull out the methane and replace it with CO_2. Even at the prevailing low prices for natural gas, revenue from the methane and geothermal heat could exceed the cost of sequestering CO_2. Whether capital costs would be passed on to ratepayers, as they often are for power plants, would depend on local regulations.

The obvious next question was whether the process could indeed pay for itself. Pope and I quickly engaged a graduate student, Reza Ganjdanesh, to find an answer.

Natural forces were in our favor. With conventional drilling, brine that rises up in a production well gradually drops in pressure and releases some of its methane. Dissolving CO_2 into brine forces out even more methane. Furthermore, many aquifers deeper than three kilometers along most of the Texas and Louisiana coasts are at high pressure, so little, if any, energy would be needed to bring the brine to the surface.

The same aquifers are also hot enough for the brine to be a good source of geothermal energy. Ganjdanesh calculated that the combined process—energy produced from methane and hot water as CO_2 was injected into the same fluid—yielded substantially more energy than was needed for the operation. This energy-positive form of geologic carbon storage could be economically attractive even in a world with no price on carbon emissions.

DRILLING DOWN THE PYRAMID

THE APPROACH also makes sense as way of providing untapped fuel. "The easy oil is gone" is a familiar refrain in the fossil-fuel industry. The easy gas is gone, too. For decades the industry drilled down into the most accessible, most concentrated and most easily extracted deposits of oil and gas, which readily rose up production pipes to the surface. As companies depleted those deposits, they moved down the "resource pyramid" to less accessible forms of fossil fuels. In the past three to five years increases in U.S. oil and gas production have come mostly from the hydraulic fracturing of deep shale. Recovering anything from this rock is slow and arduous, and the oil and gas are much less concentrated, but fracking for shale gas is the next logical step down the pyramid. We are moving there by necessity because demand keeps growing and the old, easy supplies are disappearing.

The resource pyramid has a tantalizing quality, however. The total mass of the resource typically grows as recovery gets harder. The sheer volume of natural gas locked up in shale reservoirs, for example, makes it an attractive target even though a shale gas well produces energy much less efficiently than a conventional gas well does.

Methane dissolved in brine is the next level down the pyramid after shale gas. The concentration of gas is about five times less than in shale, but the amount of methane is staggering. Estimates for the Gulf Coast alone range from several thousand to several tens of thousands of trillion cubic feet (Tcf) of methane. For perspective, in the past decade the U.S. has consumed between 20 and 25 Tcf of natural gas a year.

The size of this resource led the U.S. Department of Energy to sponsor test wells into deep brine reservoirs back in the 1970s and 1980s. The wells brought brine to the surface, but producing methane from brine could not compete on price.

Although methane from brine still cannot compete today, the other major benefit—the production of geothermal energy—could change the financial equation. On a human timescale, heat from the earth will last indefinitely. Like other subsurface resources, exploiting it requires injection and extraction wells—all off-the-shelf technology. Geothermal energy from brine is not making greater inroads primarily because the energy density of hot water is about two orders of magnitude smaller than energy obtained by burning the same volume of coal, oil or gas.

That pessimistic assessment relates to using geothermal energy to produce electricity. Yet roughly 10 percent of U.S. energy consumption is for heating and cooling the air in buildings and for heating water in homes, according to a recent DOE-sponsored reevaluation of geothermal energy. A 2,200-degree flame, like the one in a domestic gas-fired hot-water heater, is overkill. Low-intensity geothermal energy can pay if it is used for low-intensity applications such as warm air and hot water; geothermal heat pumps have been doing this successfully for homes in Europe for many years.

THREE PROCESSES BECOME ONE

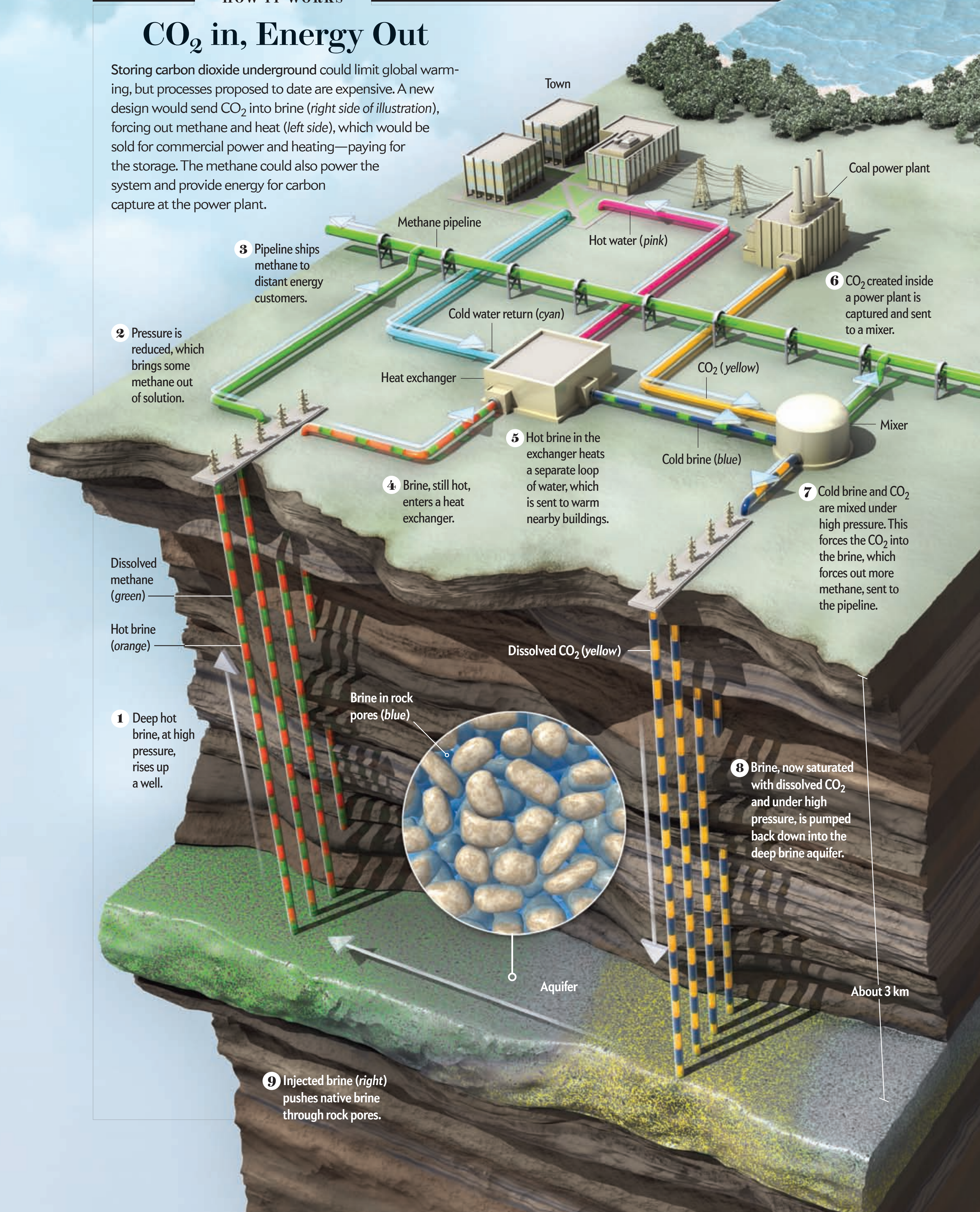
NEITHER STORING CO_2 belowground, nor tapping brine for methane fuel, nor drawing up deep brine for geothermal heat is economically viable on its own. But the combination of all three processes into one system starts to look like a three-legged stool: they become self-supporting. The ultimate question, however, is whether the system could sequester enough CO_2 to significantly reduce emissions on a national and international scale.

We recently made some calculations for the Gulf Coast. That area has a large number of fossil-fuel power plants and other industries that generate a lot of CO_2. To make an even larger dent in U.S. emissions, CO_2 could be transported from distant sources. The capital to build pipelines can be considerable, but operating costs are modest, and here again the scale is doable. For example, in the 1980s industry built more than 3,400 kilometers of

HOW IT WORKS

CO_2 in, Energy Out

Storing carbon dioxide underground could limit global warming, but processes proposed to date are expensive. A new design would send CO_2 into brine (*right side of illustration*), forcing out methane and heat (*left side*), which would be sold for commercial power and heating—paying for the storage. The methane could also power the system and provide energy for carbon capture at the power plant.



pipelines across four states near the Permian Basin in western Texas to bring CO_2 from natural, underground reservoirs to oil fields, where it is used to enhance oil recovery. The coast has enormous deep brine reservoirs. It has an extensive natural gas pipeline infrastructure that feeds the rest of the country. And it has a large population that could exploit geothermal energy.

Storing one gigaton of CO_2 a year, which is a sixth of the current U.S. emissions rate, would entail injecting and extracting about 400 million barrels of brine a day. That rate is large, but it could be achieved with about 100,000 injector and extractor wells (for reference, more than a million wells have been drilled in Texas for oil and gas). Completion of that many wells would take decades. Yet that time span would be true of any technology that averts one gigaton of CO_2 emissions a year. For example, U.S. emissions could drop that much if 200 gigawatts of electricity now generated by coal plants was instead generated by nuclear power plants. Approximately 200 large reactors would have to be built, which would certainly take decades.

The rate of energy production would also be large enough to pay for the system. Storing one gigaton of CO_2 would produce about 4 Tcf of natural gas a year, about a sixth of current U.S. consumption. The U.S. produced about 9 Tcf of natural gas from shale in 2012, which was worth $25 billion.

The rate of geothermal energy production would be significant, too. If the heat were used to provide hot air and water—and if it were also used in heat exchangers that convert warm air into cold for air conditioning—the energy captured would be about the same as the energy provided by the methane: nearly 200 gigawatts. It is unclear whether that much demand would exist along the Gulf Coast, although the many petrochemical plants there, as well as the many carbon-capture units that would be built, could use a large portion of it. Alternatively, if the thermal energy were converted to electricity with 10 percent efficiency, as is typical elsewhere, then 20 gigawatts of electricity would be produced, which would still be substantial: the U.S. has about 50 gigawatts of wind capacity.

It appears that our system has production rates big enough to support large-scale CO_2 reductions. The volume calculations seem favorable as well. Storing one gigaton of CO_2 a year for a century would sequester 100 gigatons of CO_2. It would also produce 380 Tcf of methane—less than a tenth of the methane estimated to exist in deep aquifers along the Gulf Coast. So there is ample room for storing CO_2 and an ample supply of gas.

If the methane were burned by power plants, even without capturing the CO_2 that the burning would produce, the net drop in CO_2 emissions would be 80 gigatons for a century of operation. That is a substantial drop. For example, the Union of Concerned Scientists has determined that for the world to limit atmospheric CO_2 concentration to 450 parts per million (the level generally cited to keep global temperature rise to less than two degrees Celsius), the U.S. and other industrial countries would have to reduce emissions to roughly 25 percent of 2000 levels by 2050. The U.S. would need to avoid about 150 gigatons of CO_2 between now and 2050. Even if the brine process took 20 years to reach the one-gigaton-a-year level of sequestration, it could account for 15 percent of the required U.S. reduction.

Of course, the wells and the brine-injection plants would have to be built and operated with great care to prevent methane from leaking into the atmosphere as so-called fugitive emissions. The wells would be similar to conventional onshore oil and gas wells—mature technology. The U.S. Environmental Protection Agency has a solid program for detecting emissions and their sources. And industry would not want to lose a valuable product it could sell. Processing the brine, methane and CO_2 would be similar in complexity to operations at petrochemical plants—another mature industry. Finally, because only liquids would be moving in the underground reservoir, drilling and operating the wells would be very much like conventional oil operations that have been practiced for decades. The issues associated with fracking shale—sending chemicals and large volumes of freshwater underground and the safe disposal of chemical-laden fracking fluid—would not arise for this process.

The possibility of inducing seismic activity would be extremely low, too. Recent research shows that adding large volumes of fluid into certain geologic formations—sometimes done to dispose of wastewater—might raise the risk of earthquakes. Yet the brine process is a closed loop; all the brine that gets injected is first extracted from the same formation. In this way, the original, average pressure in the formation is maintained.

Building such a system could be expensive, of course, and could raise electricity costs to consumers. But so would any serious effort that is big enough to make a meaningful difference in CO_2 emissions—whether it is building thousands of solar and wind farms or another 200 nuclear reactors to replace coal-fired power plants. [For more on costs, see More to Explore, below.]

GETTING STARTED

GIVEN OUR MANY CALCULATIONS, the brine-sequestration system seems to work on paper. Yet test plants will be vital in determining whether our system would be practical in the field. Researchers at Sandia National Laboratories, Lawrence Livermore National Laboratory and the University of Edinburgh in Scotland are designing ways to efficiently inject CO_2 into brine and extract energy. And two companies, which wish to remain nameless, are considering whether to build pilot plants along the Gulf Coast.

Gaining experience now would be prudent because if the world has any hope of limiting temperature rise caused by global warming, CO_2 emissions have to be reduced imminently.

The U.S. Gulf Coast is the ideal location to build the brine-sequestration system. The emissions problem is global, however. We do not know where else the process could be applied, but the essential element is brine containing dissolved methane, which can be expected wherever hydrocarbons are found. China and Russia, which have growing CO_2 emissions rates and large basins with oil and gas, could be good places to look first. SA

MORE TO EXPLORE

Eliminating Buoyant Migration of Sequestered CO_2 through Surface Dissolution: Implementation Costs and Technical Challenges. McMillan Burton and Steven L. Bryant in *SPE Reservoir Evaluation & Engineering,* Vol. 12, No. 3, pages 399–407; June 2009.

Coupled CO_2 Sequestration and Energy Production from Geopressured-Geothermal Aquifers. Reza Ganjdanesh et al. Presented at the Carbon Management Technology Conference, Orlando, Fla., February 7–9, 2012.

Regional Evaluation of Brine Management for Geologic Carbon Sequestration. Hanna M. Breunig et al. in *International Journal of Greenhouse Gas Control,* Vol. 14, pages 39–48; May 2013.

SCIENTIFIC AMERICAN ONLINE
For more on what the hot-brine system could cost, see **ScientificAmerican.com/nov2013/bryant**

Illustration by Emily Cooper