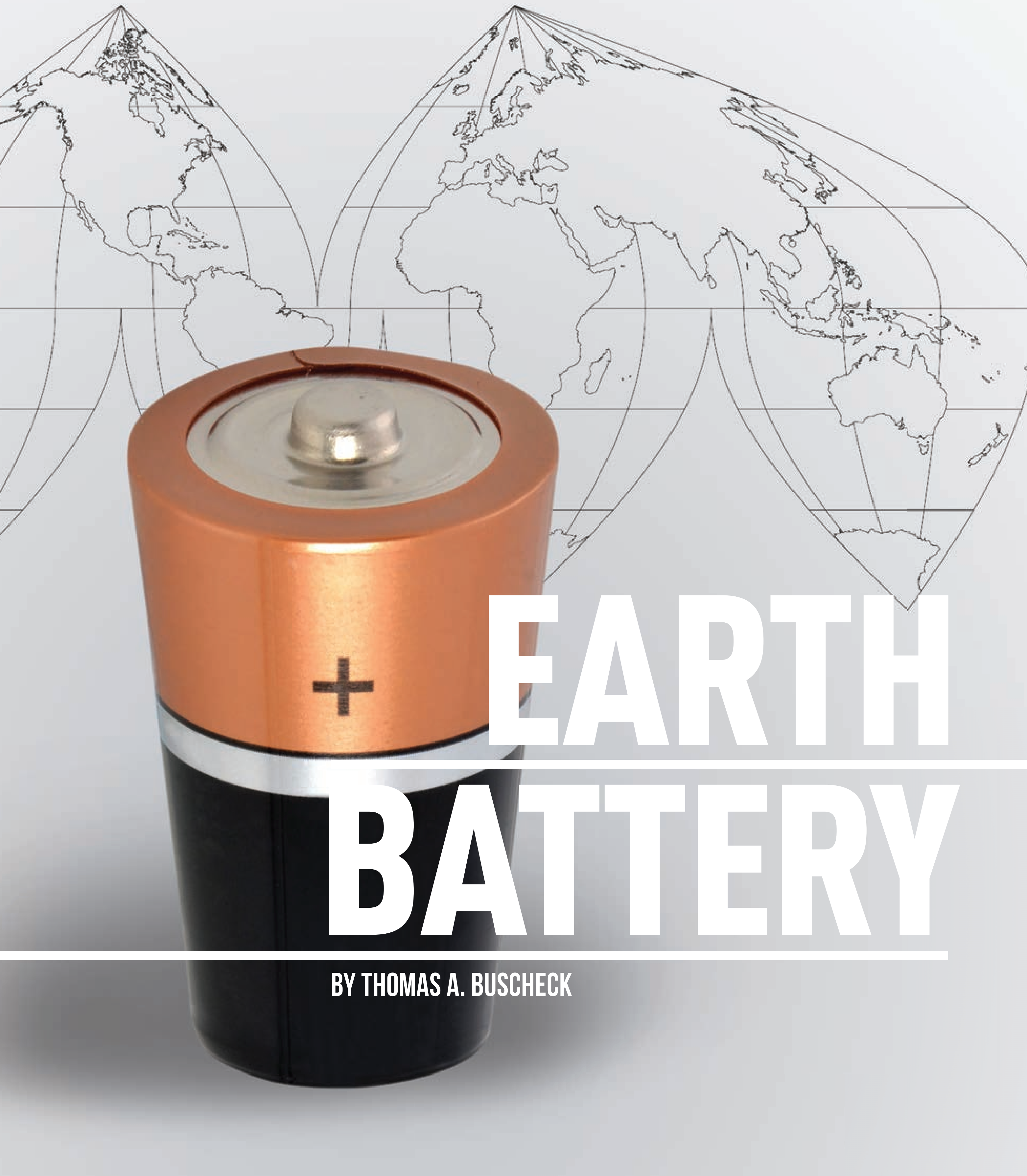

EARTH BATTERY

BY THOMAS A. BUSCHECK

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CARBON DIOXIDE SEQUESTRATION, UTILITY-SCALE ENERGY STORAGE, DISTRIBUTED POWER GENERATION—THESE ARE INDIVIDUAL PROBLEMS THAT HAVE CHALLENGED THE ELECTRICITY INDUSTRY. ONE SOLUTION MIGHT BE ABLE TO ACCOMPLISH ALL THOSE GOALS AND MORE.

INTERMITTENCY: It's the bane of renewable energy. No matter how efficient photovoltaic cells become or how much power a wind turbine can capture, someone will counter with, "What happens when the sun goes down and wind doesn't blow?" And the person who poses that question uses it as an argument in favor of traditional baseload power.

While it's true that the way the electrical grid has developed in North America and Europe doesn't lend itself to the start-and-stop, opportunistic nature of wind and solar, there are ways to meet the challenge. Electricity can be stored in batteries or water pumped uphill into reservoirs when power generation exceeds demand, to be tapped when needed. Unfortunately, utility-scale battery storage is prohibitively expensive, and pumped hydro is possible only in particular geographic locations.

What is needed is a large-scale, distributed, dispatchable energy storage system that can smooth out a renewable energy generation profile that changes by the minute as well as over the course of the day or the season.

Colleagues from Lawrence Livermore National Laboratory, the Ohio State University (led by Jeffrey Bielicki), the University of Minnesota and TerraCOH, Inc. (led by Jimmy Randolph), and I have developed a system that can do all that. What's more, this system actually sequesters carbon dioxide—a gas implicated in global climate change—as part of its normal operation.

We have modeled our system and found that, if it can be successfully demonstrated in the field, it could provide utility-scale diurnal and seasonal energy storage (many hundreds of MWe) and dispatchable power, while permanently sequestering CO$_2$ from industrial-scale fossil-energy power plants.

To be sure, an energy storage system is only as clean or as green as the primary generation it's working with. But it is going to be difficult to implement solar or wind power to a degree high enough to make a difference in global carbon dioxide emissions without utility-scale energy storage.

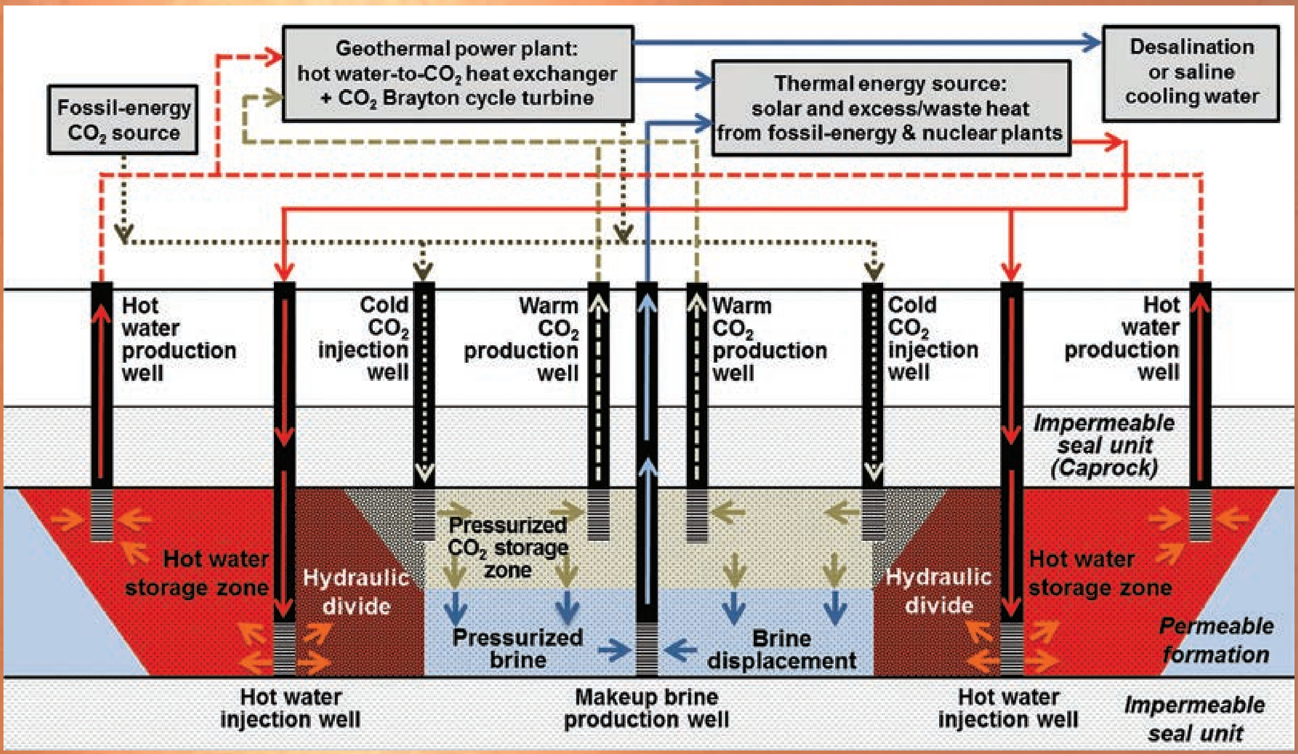
HOT ROCKS

Using geothermal heat as an energy source is an old idea. Tapping natural hot springs to provide heated waters has been done since ancient times, and the first commercial geothermal power station was built in Larderello, Italy, in 1911. Today, worldwide geothermal power capacity is estimated at 12 GWe.

While geothermal power has some advantages, because it produces no CO$_2$ emissions, requires no fuel, and is capable of constant production, it is limited to certain geological formations. Specifically, wells must be able to tap geothermally heated water or steam and bring it to the surface to turn a turbine.

To overcome this limitation, researchers have studied engineered (or enhanced) geothermal systems, often called EGS for short. The concept involves drilling miles deep into dry hot strata that underlie large portions of continents. Often, these rocks are impermeable, so they would have to be fractured via means now used to exploit shale gas reserves. In most EGS schemes, water would be pumped into these fractured rocks, heated to high temperature, and then brought to the surface via a borehole.

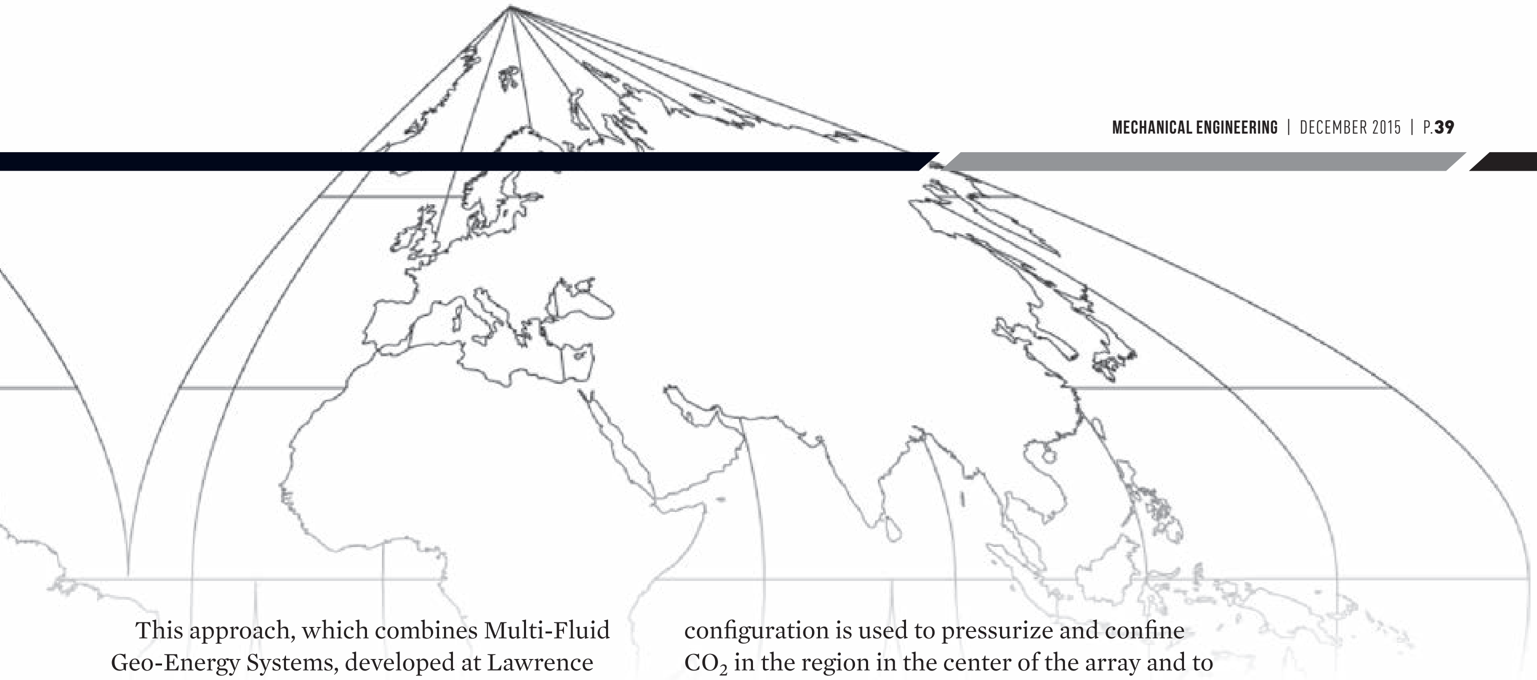
> IT IS GOING TO BE DIFFICULT TO IMPLEMENT SOLAR OR WIND POWER TO A DEGREE HIGH ENOUGH TO MAKE A DIFFERENCE IN GLOBAL CARBON DIOXIDE EMISSIONS WITHOUT UTILITY-SCALE ENERGY STORAGE.



A Multi-Fluid/CPG system can store energy from thermal power plants, as shown in this schematic. Supercritical carbon dioxide is injected into the underground reservoir to create a buoyant, pressurized plume that displaces the pre-existing brine. That brine flows to the surface in separate wells and is then heated and reinjected in the reservoir to store thermal energy. The reinjection wells are arrayed in a ring shape to create a hydraulic divide that pressurizes the CO$_2$, which functions as cushion-gas shock absorber to enable the system to be charged or discharged depending on the balance of energy supply with demand. To allow the CO$_2$ plume to safely expand without too much overpressure, a small portion of the cool brine exiting the geothermal power plant may be diverted for beneficial use. Depending on the geology, the system may also employ horizontal wells.

While water is a familiar working fluid, it isn't optimal for this kind of system. A better option is supercritical carbon dioxide, a form of the compound that has been placed under enough pressure to blur the distinction between liquid and gas. Compared to water, supercritical CO$_2$ has a lower kinematic viscosity, allowing for effective heat advection despite its relatively low heat capacity, and a higher thermal expansibility, generating a much stronger thermosiphon effect looping through the injection well, the reservoir, the production well, and turbine. Because of this, the need for pumps to drive the recirculation of the fluid through the underground reservoir can be reduced or even eliminated.

Still, engineered geothermal systems are limited in scale, due to the impermeable nature of the strata in which they are generated. My colleagues and I have looked instead at utilizing reservoirs residing in geological layers made from sedimentary rock, which is permeable to CO$_2$ as well as the brine (saline water) contained in that rock. These rocks can hold much more carbon dioxide and can be naturally more extensive than engineered systems in crystalline rock. Because sedimentary rock is softer than the crystalline rock where most geothermal systems reside, such strata are easier to drill into and reach than the deeper dry rock layers, though they aren't as hot, generally only around 100 °C.



This approach, which combines Multi-Fluid Geo-Energy Systems, developed at Lawrence Livermore National Laboratory, with CO_2 Plume Geothermal, or CPG, which was developed by Jimmy Randolph, Martin Saar, and colleagues at the University of Minnesota, has some interesting aspects. For one, the kind of permeable sedimentary rock that it utilizes is found all over the world—including under about half of North America. But more intriguing, these strata can hold a large amount of carbon dioxide and have been targeted as potential reservoirs for CO_2 sequestration, a concept for banking CO_2 outside of the atmosphere where it acts to promote global warming. Second, this approach takes the biggest challenge facing geologic CO_2 sequestration—overpressure—and turns it into an asset to efficiently produce multiple fluids (CO_2 and naturally occurring brine) to recover heat.

For our Multi-Fluid/CPG approach to have the greatest impact, our models indicate that trying to merely tap geothermal heat as an energy source does not take full advantage of our approach. Instead, these reservoirs may be best used as vast batteries, storing heat and pressure during periods of energy overproduction (say, when strong winds blow on winter nights, producing an overabundance of wind power) and releasing that energy when such intermittent resources are unavailable.

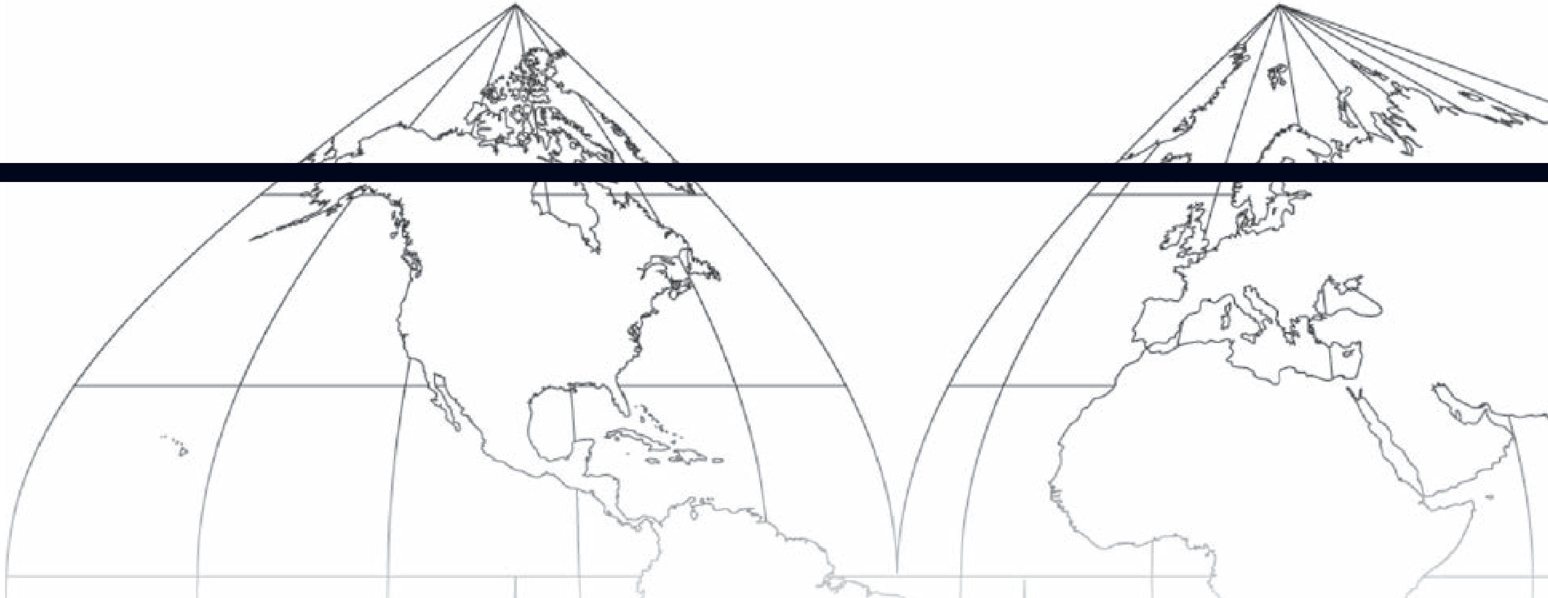
ENERGY BANK

Operationally, a Multi-Fluid/CPG system would be radically different from traditional power plants or energy storage systems, such as pumped hydroelectric. For instance, unlike a coal-burning power plant that occupies a few hundred acres or a wind farm that may be spread across a few thousand, for a Multi-Fluid/CPG system there would be very little to see above the ground surface. Most of our system resides below the ground surface, consisting of horizontal injection and production wells arrayed in concentric rings that could be five miles or more across. This ring configuration is used to pressurize and confine CO_2 in the region in the center of the array and to pressurize brine between the outer two rings. In our modeling studies we increase the fluid pressure in the strata to 7 to 10 MPa, or around 70 to 100 atmospheres, which is enough to efficiently recirculate the working fluids and to store energy, but not too much to overpressure the overlying confining layer and break it.

While CO_2 captured from a fossil energy power plant would be injected continuously, brine produced from the storage formation would be injected intermittently from the surface using power that's produced in excess of demand. That could be power from wind turbines, especially at night when demand is low, or solar power during sunny spring weekends. Traditional baseload electricity can also outstrip demand at certain hours or times of the year. Regardless of the source, this power would be stored in the form of pressurized CO_2 and brine.

> THESE RESERVOIRS MAY BE BEST USED AS VAST BATTERIES, STORING HEAT AND PRESSURE DURING PERIODS OF ENERGY OVERPRODUCTION AND RELEASING THAT ENERGY WHEN SUCH INTERMITTENT RESOURCES ARE UNAVAILABLE.

When demand for electricity increases, the brine pumps would be shut off and the pressurized brine and CO_2 would rise up the production wells to the surface. The brine could be the heat source for an organic Rankine cycle binary power generation system, where the geothermally warmed water would evaporate a working fluid. The supercritical CO_2, on the other hand, could be used to drive a turbine directly and with greater



efficiency. Both fluids would be recirculated back down to the storage strata. Because of the Joule-Thomson cooling effect, CO_2 will always be produced at a cooler temperature than produced brine; thus, the hotter brine can be used to boost the temperature of the CO_2 prior to sending it through the turbine. Transferring brine enthalpy to supercritical CO_2 is more efficient than using it in an organic Rankine cycle power system.

We modeled this simplest version of the Multi-Fluid/CPG system, with the storage layer at depths ranging from 3,000 to 5,000 meters below the surface, corresponding to rock temperatures between 120 °C and 200 °C. As one might imagine, the power produced is a function of the depth of the reservoir, though the net storage rate of CO_2 injection is also important. To keep pressure within an optimal and safe operational range, we divert a small portion of the produced brine for beneficial consumption, such as for desalination or for use as saline cooling water. For our reference system, one that's about five miles across and having been operated for about 10 years, the combination of pressure from the pumped fluids and heat drawn from the geothermally heated rock allows for as much as 500 MWe of power to be produced during peak demand hours.

The power production is sensitive to the heat of the geothermal resource, with the shallower strata unable to produce as much net power. However, if the system was coupled with a thermal power station—such as a nuclear plant or a concentrating solar power plant—the brine could be stored at an elevated temperature, say 200 to 300 °C. The stored heat would enable the Multi-Fluid/CPG system to operate where geothermal power would not be feasible. We modeled a case where 300 °C brine is pumped into relatively shallow strata and found that in time, the stored brine could be returned to the surface at 280 to 290 °C, meaning 90 percent of the stored heat could be recovered for power production.

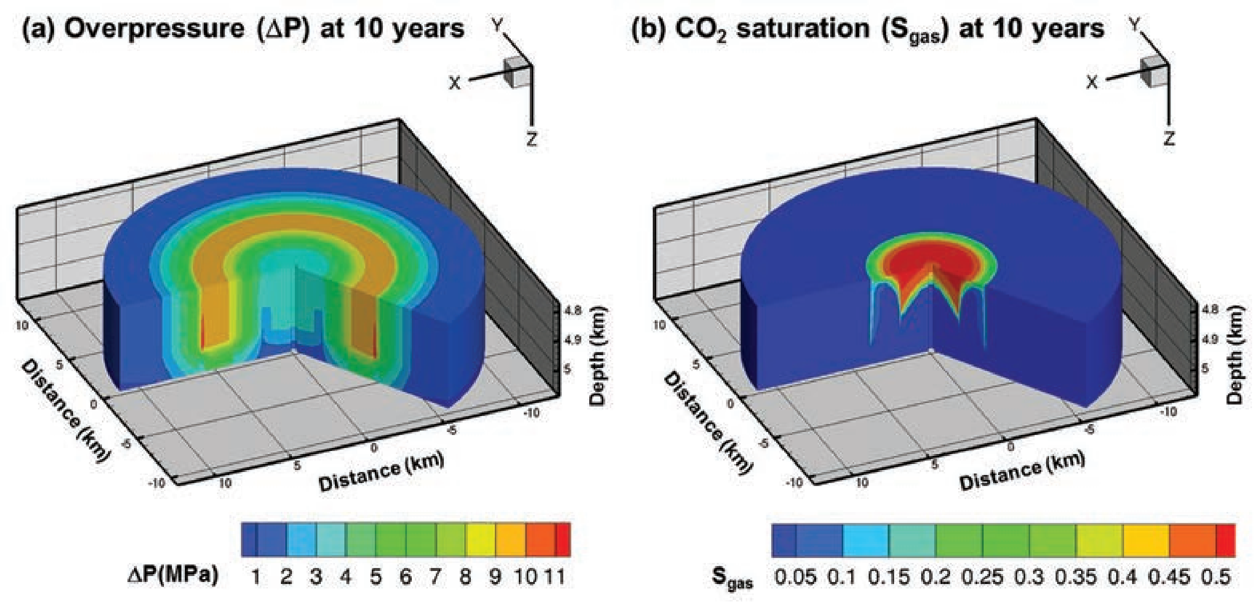
TO LEARN MORE

- T.A. BUSCHECK, J.M. BIELICKI, M. CHEN, Y. SUN, Y. HAO, T.A. EDMUNDS, M.O. SAAR, AND J.B. RANDOLPH, "INTEGRATING CO_2 STORAGE WITH GEOTHERMAL RESOURCES FOR DISPATCHABLE RENEWABLE ELECTRICITY," ENERGY PROCEDIA, 63, 7619-7630 (2014)
- T.A. BUSCHECK, J.M. BIELICKI, T.A. EDMUNDS, Y. HAO, Y. SUN, J.B. RANDOLPH, AND O.M. SAAR, "MULTI-FLUID GEO-ENERGY PRODUCTION AND GRID-SCALE ENERGY STORAGE IN SEDIMENTARY BASINS," GEOSPHERE (IN PRESS)

Our approach to utility-scale thermal energy storage can address both diurnal and seasonal supply/demand mismatches. This would be particularly useful for an inflexible baseload thermal power station, such as nuclear, that is unable to cycle its power to match demand, or, in the case of an intermittent concentrating solar power plant, reliably dispatch power when demanded, such as on cloudy days or in winter. Thus, thermal energy storage would add reliability and baseload capability to solar power.

One way to imagine the storage cycle is to couple the Multi-Fluid/CPG system to a 1,300 MWe nuclear power plant. Over the course of a day, the plant would send heat into geologic storage for 12 hours and use it to run steam turbines the other 12 hours. The Multi-Fluid/CPG system, running at 90 percent round-trip efficiency, could take the stored thermal energy to run at a constant 585 MWe; it could also be run at 1,170 MWe for 12 hours and 0 MWe for the other 12 hours. Because the thermal energy is stored under pressure, other combinations are possible, including much higher peaking capacity. Although the plant would run like a baseload power plant, the power would be as dispatchable as a peaking plant; however, our system could operate continuously to better utilize the capital investment of the plant, unlike a peaking plant that is idle much of the time.

Multi-Fluid/CPG systems would provide another valuable service: CO_2 sequestration. According to our model, a Multi-Fluid/CPG system in a



A numerical simulation of a Multi-Fluid/CPG system is shown after 10 years of operation. The pressure in excess of initial fluid pressure in the reservoir is depicted on the left, and the hydraulic divide in the system is formed at the orange-colored region of maximum overpressure. The hydraulic divide confines the supercritical carbon dioxide, and the figure on the right shows the fraction of the rock pore space that is filled by the CO_2. The top of the contour plots corresponds to the interface between the permeable reservoir rock and the overlying impermeable caprock.

125 m thick reservoir would store 120 million tons of CO_2, or about 4 million tons a year for 30 years. That's equivalent to the CO_2 produced by a 600 MWe coal plant. That's essentially like erasing the CO_2 impact of a coal-fired plant while simultaneously improving the reliability of an electric grid increasingly being fed by renewables.

INCREASING RELIABILITY

What's more, because the Multi-Fluid/CPG system relies on the injection of carbon dioxide, the cost of sequestration is turned into an operational investment. Just as enhanced oil recovery has made geological CO_2 sequestration economically viable in the petroleum industry, Multi-Fluid/CPG can make it profitable to lock away CO_2 that would otherwise be emitted.

Storing energy in the Earth via Multi-Fluid/CPG doesn't solve all the problems with the intermittency of renewable energy, but it does increase the hourly, daily, and seasonal reliability of an electrical grid that is deeply reliant on solar or wind power. And unlike those renewable sources, which by necessity must be sited where the sun shines the strongest and the wind blows the hardest, Multi-Fluid/CPG systems can be built anywhere there is suitable geological formations—which includes about half of the United States.

To be sure, much research and development needs to be done to confirm the promise of Multi-Fluid/CPG. But the concept is based on proven technology; there are no obvious showstoppers.

Engineers have spent decades pacing the ground, looking for a means to make intermittent renewable energy systems compatible with an electrical grid that was designed for baseload power. I believe that the answer to their quest was just below their feet. **ME**

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