The Renewable-Energy Revolution Will Need Renewable Storage

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Matthew Hutson

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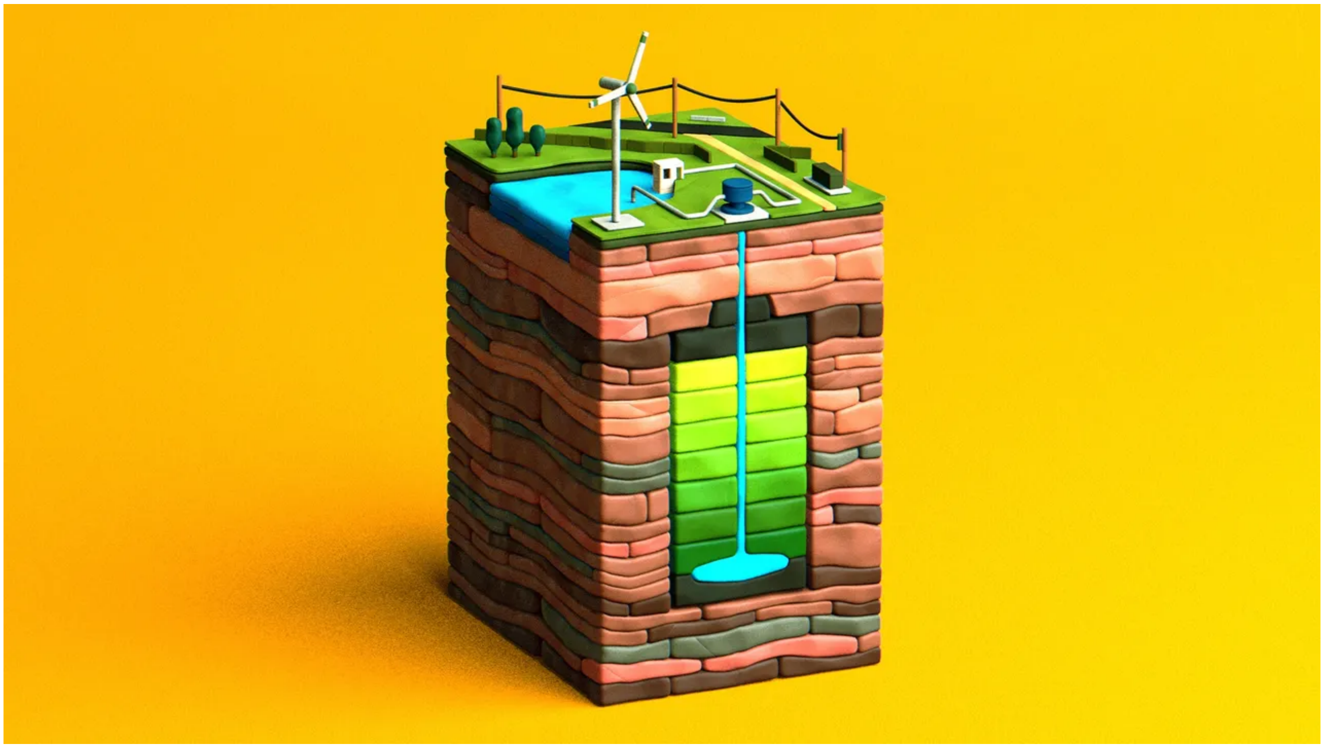

Content

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The German word *Dunkelflaute* means "dark doldrums." It chills the hearts of renewable-energy engineers, who use it to refer to the lulls when solar panels and wind turbines are thwarted by clouds, night, or still air. On a bright, cloudless day, a solar farm can generate prodigious amounts of electricity; when it's gusty, wind turbines whoosh neighborhoods to life. But at night solar cells do little, and in calm air turbines sit useless. These renewable energy sources stop renewing until the weather, or the planet, turns.

The dark doldrums make it difficult for an electrical grid to rely totally on renewable energy. Power companies need to plan not just for individual storms or windless nights but for *Dunkelflaute* that stretch for days or longer. Last year, Europe experienced a weeks-long "wind drought," and in 2006 Hawaii endured six weeks of consecutive rainy days. On a smaller scale, factories, data centers, and remote communities that want to go all-renewable need to fill the gaps. Germany is decommissioning its nuclear power plants and working hard to embrace renewables, but, because of the problem of "intermittency" in its renewable power supply, it remains dependent on fossil fuels—including imported Russian gas.

The obvious solution is batteries. The most widespread variety is called lithium-ion, or Li-ion, after the chemical process that makes it work. Such batteries power everything from mobile phones to electric vehicles; they are relatively inexpensive to make and getting cheaper. But typical models exhaust their stored energy after only three or four hours of maximum output, and—as every iPhone owner knows—their capacity dwindles, little by little, with each recharge. It is expensive to collect enough batteries to cover longer discharges. And batteries can catch fire—sites in South Korea have ignited dozens of times in the past few years.

Venkat Srinivasan, a scientist who directs the Argonne Collaborative Center for Energy Storage Science (*ACCESS*), at the Argonne National Laboratory, in Illinois, told me that one of the biggest problems with Li-ion batteries is their supply chain. The batteries depend on lithium and cobalt. In 2020, some seventy per cent of the world's cobalt came from the Democratic Republic of the Congo. "Unless we have diversity, we're going to be in trouble," Srinivasan said. Any disruption to the supply chain can strongly affect prices and availability. Moreover, a lot of water and energy are required for mining the metals, which can cause environmental damage, and some cobalt-mining operations involve child labor. Experts doubt that Li-ion prices will drop more than thirty per cent below their current levels without significant technological advancements—a drop that is still too small, according to the Department of Energy. We need to expand our capacity; by one estimate, we'll require at least a hundred times more storage by 2040 if we want to shift largely to renewables and avoid climate catastrophe. We may somehow find clean and reliable ways to mine, distribute, and recycle the ingredients for Li-ion batteries. And yet that seems unlikely. Although we usually think about renewable energy in terms of its sources, such as wind turbines and solar panels, that's only half the picture. Ideally, we'd pair renewable energy with renewable storage.

We already have one kind of renewable energy storage: more than ninety per cent of the world's energy-storage capacity is in reservoirs, as part of a remarkable but unsung technology called pumped-storage hydropower. Among other things, "pumped hydro" is used to smooth out spikes in electricity demand. Motors pump water uphill from a river or a reservoir to a higher reservoir; when the water is released downhill, it spins a turbine, generating power again. A pumped-hydro installation is like a giant, permanent battery, charged when water is pumped uphill and depleted as it flows down. The facilities can be awe-inspiring: the Bath County Pumped Storage Station, in Virginia, consists of two sprawling lakes, about a quarter of a mile apart in elevation, among tree-covered slopes; at times of high demand, thirteen million gallons of water can flow every minute through the system, which supplies power to hundreds of thousands of homes. Some countries are expanding their use of pumped hydro, but the construction of new facilities in the United States peaked decades ago. The right geography is hard to find, permits are difficult to obtain, and construction is slow and expensive. The hunt is on for new approaches to energy storage.

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Quidnet, a Houston-based startup, is one of many companies exploring the possibilities. Last month, I sat in an F-150 King Ranch pickup with Scott Wright, its vice-president of operations, and Jason Craig, its C.O.O., as we drove to one of its test sites, on a farm west of San Antonio. Fields and billboards whizzed by as Craig explained, from the back seat, that Quidnet had patented a new kind of pumped hydro. Instead of pumping water uphill, the company's system sends it underground through a pipe reaching at least a thousand feet down. Later, the system lets the Earth squeeze the water back up under pressure, using it to drive generators. Wright and Craig are veterans of the oil and gas industry, and Quidnet's technology is like a green riff on fracking. In that technique, fluid is injected underground, where it builds up pressure that fractures rocks, releasing natural gas. Quidnet uses some of the same equipment and expertise, but with a different goal: the water is meant to be sandwiched between layers of rock, forming underground reservoirs that can be released on demand.

As we drove, I asked about the blackouts Texas experienced in February of 2021, when a winter storm shut down gas plants for several days and left millions without power. More than two hundred people died. The crisis had many causes, including the fact that Texas is the only state whose power grid isn't connected to grids in other states. "We were pulling buckets of water out of the neighbor's pool to get toilets to flush," Wright said. "It definitely screams for some way to store power to lessen the burden on the grid in times like that."

The artificial underground reservoirs created by companies like Quidnet are known to engineers as "lenses," because of their shape. ("I say whoopee cushion and people don't like it," Craig said.) Initially, Quidnet encountered skepticism about its ability to form lenses of the right size and shape. By the time I visited, however, it had successfully completed multiple pumping cycles in Texas, Ohio, and Alberta. The company has received thirty-eight million dollars in private and government funding, including contributions from Breakthrough Energy Ventures, established by Bill Gates.

Quidnet has benefitted from an energy-storage gold rush. In 2018, the Department of Energy awarded thirty million dollars in funding to ten groups, including Quidnet, through a program called Duration Addition to electricitY Storage, or *DAYS*. Before leaving office, President Donald Trump signed into law the Energy Act of 2020, which included the bipartisan Better Energy Storage Technology (*BEST*) Act, authorizing a billion dollars to be spent over five years on the "research, development, and demonstration" of new energy-storage technology. Many states are now setting storage-capacity targets, and in 2018 the Federal Energy Regulatory Commission issued Order 841, which integrates stored energy into the wholesale electricity market. "There's been a recognition that this is a technology whose time has come," Jason Burwen, of the American Clean Power Association, told me. But a vast distance separates an engineer's whiteboard from reality. Many renewable-storage technologies receiving funding will turn out to be too impractical, expensive, or inefficient for widespread adoption.

As we approached the farm, Craig mused on the raw physicality of many companies' approaches. The basic principles are ones you might recall from high-school physics. If you put effort into lifting an object, it stores potential energy; if you then let that object fall, its potential energy becomes kinetic energy, which is capable of powering a generator and creating electricity. The same holds for many physical actions. In addition to lifting weights, energy-storage companies are compressing air or water, or making objects spin, or heating them up. If you use clean energy to do the initial work and find a green way to store and release it, you've created an ecologically responsible battery alternative.

"I'm kind of surprised and encouraged that the solutions to the long-duration-energy-storage problem could be the caveman stuff," Craig said. Batteries depend on "pretty sophisticated electrochemistry that quickly gets outside of what I understand. And yet the solutions may be picking up heavy stuff with cranes, picking up the earth with a hydraulic jack. I think there's some fellas in Nevada that are putting rocks in a train and rolling it uphill, then they come back down. Like, Fred Flintstone would be comfortable with most of this stuff. It could be the way."

We pulled into the farm's long drive. A kettle of vultures circled overhead.

"You know what that means?" Craig asked.

"The last reporter who came out here?" I said.

They laughed. "That's right. Too many bad questions."

I already had one in mind. Was I about to see part of the future of green energy, or a curious and short-lived experiment in rural Texas?

Until recently, we didn't have to think much about new ways to store our energy. Fossil fuels are a prehistoric energy repository, and we could unlock their energy by burning them and driving generators. There was always more fuel to burn. "Almost all electricity in the world is used as it's made," Bill Gross, a longtime investor in solar power and a co-founder of Energy Vault, one of the most highly capitalized new energy-storage companies, told me. Most power that isn't consumed immediately is lost. The problem is that, with many technologies, "it actually costs more to store electricity than to make it," he said. In many cases, solar and wind have become less expensive than coal and gas. But add the cost of storage, and renewables can lose to fossil fuels.

Energy is stored all around us, in all sorts of ways. A bottle of fizzy water in your fridge holds energy under pressure; a tower of books contains energy, which is released when it falls. On a larger scale, volcanic eruptions and avalanches release stored energy. But energy storage is most useful when it is predictable, convenient, and dense, packing lots of power into a small space. Climate change notwithstanding, fossil fuels meet all these requirements: by burning just a gallon of easily transported gasoline, you can release enough energy to move thousands of gallons of water from the bottom of a pumped-hydro station to the top.

Today's Li-ion batteries are low-density by comparison, and renewable-storage systems also struggle to achieve density, convenience, and scale. The basic technology behind compressed-air energy storage goes back decades, and can involve pumping air into underground caverns, natural or artificial, then letting it out again. The first underground compressed-air facility was completed in 1978, in Germany; such systems can store and release vast amounts of energy. But, like pumped hydro, compressed-air facilities require the right geography and are expensive to build. They are also inefficient—typically, only half the energy put into pressurizing the gas can be retrieved.

Engineers are trying to improve density and efficiency. A Toronto-based company called Hydrostor has received more than three hundred million dollars in funding and is developing projects in California, Australia, and other places, to be brought online in the next five years. It stores compressed air in tanks, and holds on to the heat released during the air-compression process, which it then reapplies to the air during expansion, supercharging its ability to drive a turbine and generate electricity. A British company, Highview Power, is taking a more extreme tack, cooling air to more than three hundred degrees below zero, at which point it becomes a liquid. Liquid air is dense, and when Highview warms it, it gasifies rapidly, spinning turbine blades. Colin Roy, Highview's executive chairman, told me that, when the company opens its tanks, air "explodes out with violent force." It has built a prototype liquid-air system and is developing commercial plants in England and Spain.

Quidnet, too, is producing a refinement of pressure-based technology. At the company's test site, we were greeted by Jacob and Sadie Schweers, the farm's owners. About a year earlier, Quidnet had dispatched a drilling rig—a seventy-foot mast attached to a truck—to their property. Now a blue wellhead stood about ten feet tall, near a pump house the size of a shipping container, several yellow tanks, and a bunch of hoses. Water could be pumped from the tanks into the well, where it would be stored under pressure; then it could be released back to the tanks. Last month, Quidnet announced a pilot program to provide stored-energy technology to a utility in San Antonio.

We stepped inside the pump house to admire the pistons, the flywheel, and something called a pulsation dampener. A yellow five-hundred-horsepower diesel engine sat quietly in the back, ready to run the pump. "I love big machines and loud things and the smell of oil," Wright said. In a commercial version of the system, an electric motor, ideally powered by clean energy, would pump the water, and act as a generator when the water returned.

As we walked back outside, into the hot sun, Wright gestured toward ten separate PVC pipes sticking out of the ground. They indicated the subterranean presence of tiltmeters, instruments for assessing the size and character of the lens by tracking the displacement of the rock; they can even sense the tidal tugging of the moon. We stood and chatted, and Craig said that the tanks would eventually be replaced by an attractive pond. Sadie Schweers told us that she likes to picture the whole farm running on solar panels and a Quidnet well.

People who work in energy often speak of the grid as if it had its own hungers and quirks. “The grid wants a diversity of assets,” Mateo Jaramillo, the C.E.O. of Form Energy, which makes “iron-air” batteries, told me. (The technology, which stores energy by rusting and un-rusting metal in a cycle, is one of a number of theoretical alternatives to Li-ion.) There’s room for many kinds of solutions in the clean grid to come; at the same time, the landscape is hyper-competitive. “Everyone’s competing against pumped-storage hydro and lithium-ion,” Scott Litzelman, the director of *DAYS*, the Department of Energy program, told me. “Lithium-ion is just so dominant, given that there’s such a significant supply chain and manufacturing base.” Referring to the non-battery startups, he said, “You have these other nascent technologies that could be more competitive if they can get to scale. That’s the challenge across the industry. Everyone’s trying to get to that point to prove, first, the technical viability and the cost potential, and then prove this not in the laboratory, but at a massive field site.”

Shirley Meng, a materials scientist and engineer at the University of Chicago, told me that the world needs “a whole suite of storage methods.” Not all methods will find a niche, but, she said, “I think we are way, way underinvested. Because we are really imagining trying to rebuild the entire grid system.” Nathan Ratledge, a clean-energy researcher at Stanford, told me that energy storage could play an especially important role in places where power grids are still being built. Many countries in the developing world have a chance to leapfrog fossil fuels altogether, heading straight to renewable power, which is cheaper and less polluting. But a grid with a larger proportion of wind and solar requires more storage capacity to overcome intermittency. Renewable storage is “a win-win-win for the Global South,” Ratledge said. “It’s basically allowing people to jump really fast into the twenty-first century without dealing with all the outdated junk we built in the seventies and eighties and nineties.”

Driving back in Wright’s truck, I thought about how things might look if Quidnet’s wells make headway. Today’s pumped-hydro plants form picturesque lakes on the Earth’s surface, but approaches like Quidnet’s would create reservoirs of pressurized energy beneath it. The company envisions terrain dotted with wellheads about half a mile apart, and a pond for every four. Wind turbines might rise skyward. The Earth itself would be a kind of giant battery.

Bill Gross, the Energy Vault co-founder, began looking into energy storage after a long career in West Coast tech, during which he started a string of successful dot-coms and solar-power companies. He wondered if he could construct a system based on the same principles as pumped hydro, but with solids instead of liquids. Rather than pumping water uphill and releasing it downhill, could you stack weights using clean energy, then generate power by using pulleys to lower them? “I wanted to make a sort of virtual mountain,” he told me.

Gross and a civil engineer, Andrea Pedretti, started looking at options. They wanted to “build height cheaply,” Gross said. Steel was expensive. So was concrete, and producing it emitted carbon. They began working with a company called Cemex on the use of a “superplasticizer”—a polymer capable of holding dirt together, often used to build roads in low-income countries. Mix superplasticizer with local dirt, water, and a bit of cement, and you can make cheap blocks on site. “So we can basically make a mountain out of dirt,” Gross said. “And we can make that mountain every day, and unbuild that mountain every day.” Matching pumped hydro in scale would be ambitious. But even midsize mountains might be able to stash energy made at co-located solar farms or nuclear plants, or keep the servers running at data centers. Gross and Pedretti founded Energy Vault in 2017, with Robert Piconi, the company’s C.E.O. It has offices in Los Angeles and Switzerland.

Energy Vault’s first attempt at a system was EV1, a looming, Transformer-like tower crane with six arms. The idea was that such a crane would stack blocks in a wall around itself, then unstack them. Observers on the Internet had a field day pointing out what they perceived to be the system’s impracticality. (A YouTube video titled “The Energy Vault Is a Dumb Idea, Here’s Why” has been viewed two million times.) In any case, the company moved on to a new, enclosed design, called EVx. In renderings, it resembles a boxy automated warehouse forty stories tall. Elevators will use clean power to lift blocks weighing as much as thirty tons and put them on trolleys, which will move them toward the middle of the structure. When energy is needed, the blocks will be moved back to the elevators. As they descend, the elevators will power generators, producing new electricity. Energy Vault claims that the system will have a high round-trip efficiency, regenerating a great deal of the electricity it consumes. Yet even so EVx will have to move thousands of heavy blocks to store and release significant amounts of energy. Ordinarily, our energy use is an abstraction; Energy Vault’s approach reveals it in stark, physical terms.

The EVx demo is being developed in a bucolic Swiss mountain valley in the shadow of EV1. In March, Piconi gave me the sales pitch. After donning hard hats, vests, and eye protection, we stopped by the block-making machine, a big blue steel box. It compresses the blocks’ ingredients using seven thousand tons of force, then flips them upright, making a new one every fifteen minutes. “You don’t go buy this at Walmart,” Piconi said.

Nearby, we saw two of the trolleys that will carry the blocks to and from EVx’s elevators. I placed my hand on one of the hard plastic wheels. The company was still experimenting with trolley materials, Piconi said: “A lot of what we do is material science.” We headed to the control room, which turned out to be a trailer fitted with computers, where Frank Tybor, Energy Vault’s vice-president of engineering, sat with his Australian shepherd, Sydney. Previously, Tybor had been the principal engineer for launch and landing pads at SpaceX. (Sydney had “been in enough rocket control rooms that if you count backwards from ten to zero and nothing happens she gets upset,” Tybor said.) Energy Vault was similar to SpaceX, he told me, in that “it seems large and industrial, but the secret sauce is how we make it all work robustly.” On a big screen, we saw a car-size block trundling back and forth on a trolley as sensors gathered data about wear and tear.

Outside, Piconi and I went to find the trolley we’d seen on the screen. We walked past tall blocks of various compositions, as though we were at a construction site for the pyramids, before coming upon Vahe Gabuchian, the test engineer who was controlling the trolley. He had studied fracture mechanics at Caltech, and wanted to know if any of the components would crack during thousands of miles of rolling and vibration. Nearby, a four-story structure made of I-beams offered a tiny preview of what a final EVx might look like. The warehouse, if it works, will be a moving puzzle. Software will need to orchestrate the motions of elevators and trolleys to keep power consistent as blocks accelerate, decelerate, and are lifted and lowered.

Energy Vault's lead mechanical engineer, Al Sokhanvari, came over. He'd spent thirty years completing aerospace projects for NASA and the Defense Advanced Research Projects Agency, and had helped build the fountain at the Bellagio, in Las Vegas. ("But this is the coolest, you have to admit," Piconi said.) In a sense, an EVx building would be like a fountain, but with blocks of earth circulating instead of water. When it was storing a lot of power, the warehouse would be top-heavy, with many tons of blocks on its upper floors; the blocks would flow to the bottom as power was withdrawn. "So you have to make it something that is actually breathing with weights in and out," Sokhanvari said. Such a building would be like "a living thing."

Developing energy storage is risky. Unlike Quidnet, Energy Vault is publicly traded; it has a market cap of more than a billion dollars, but its future is uncertain. The technology is still in its early stages, and it can be hard to tell how much of the excitement about the company reflects salesmanship, as opposed to viable engineering. No one has built a facility like EVx before, and the system contains moving parts that might break down more than expected. Venkat Srinivasan, the ACCESS director, noted that lithium-ion batteries are portable and, crucially, reliable. "If you're operating on the grid, reliability is No. 1, 2, and 3, right?" he said. Utilities want products and companies that have a decade's worth of data behind them. Investors are putting a lot of money into new energy firms, but "some of these bets won't go the way we think," he said. "There'll be multiple reasons for it. Some of it could be technological, but it's also execution."

Li-ion batteries, despite their flaws, are a known quantity. The method being developed by Energy Vault isn't. Still, the company isn't alone in pursuing what's known as "gravity storage." Gravitricity, based in Scotland, recently concluded a demonstration that involved hefting a fifty-ton block up a tower, two stories at a time; it now plans to raise and lower single, thousand-ton blocks inside disused mine shafts. Two other companies, Gravity Power, in California, and Gravity Storage GmbH, in Hamburg, aim to place a massive weight at the bottom of a shaft and then pump water underneath to lift it. To withdraw energy, they'll let the weight push the water down into a pipe and through a turbine. RheEnergise, based in Montreal, has come up with yet another take on pumped hydro, centered on a fluid that the company invented called R-19, which is two and a half times as dense as water; its system will move the fluid between tanks at the top and bottom of an incline. The work is still at the crowdfunding stage.

Just as you can store potential energy by lifting a block in the air, you can store it thermally, by heating things up. Companies are banking heat in molten salt, volcanic rocks, and other materials. Giant batteries, based on renewable chemical processes, are also workable. In so-called flow batteries, tanks can be used to manage electrolytes, which hold a charge. In hydrogen storage, electrolysis is used to separate hydrogen from oxygen in water; the hydrogen is then cached underground, or in aboveground tanks, as gas or liquid or part of ammonia. When it's recombined with oxygen in a fuel cell, it forms water again and releases electricity.

Srinivasan told me that he often looks at new proposals and thinks, "Hey, that could be part of the solution." Litzelman, of the Department of Energy, said that the range of ideas being pursued "suggests that no one has found a combination that hits every single requirement—very low cost, production at scale, high performance." In one likely scenario, many technologies will proliferate, each solving a different problem. Some will ameliorate *Dunkelflaute*. Others will help the grid avoid congestion, or hold energy so that it can be bought and sold. Still others will assure "power quality," smoothing out second-to-second electrical fluctuations. One smoothing technology currently in use is the flywheel: in advanced versions, masses of metal weighing a ton or more levitate in vacuums by means of magnets, as electric motors rotate them tens of thousands of times per minute. Generators then slow them down, retrieving their energy. ("The grid loves spinning metal," one engineer told me.)

Litzelman believes that energy-storage systems will eventually bring down the over-all cost of decarbonization, but acknowledged that they might not be an easy sell. "The grid, in quotation marks, is not a customer," one of his colleagues likes to say. Real customers are independent power producers, utilities, and companies that run factories or data centers. One challenge is figuring out who pays for what. It also matters how well a solution meshes with the grid—and that depends on many factors. Jaramillo, of Form, the iron-air-battery company, said, "You cannot look at one spec sheet and compare it to another spec sheet and say, 'Ah, better round-trip efficiency, this one's better.' " His company has used computer models that draw on data about weather and markets to figure out how its technologies might fit. Jaramillo happens to have a master's in theology—a discipline that he said was surprisingly useful in understanding energy-storage systems. "All storage systems have trade-offs," he said. "It's not so different from humans. I am far from perfect. I'm very happily married only because my wife tends to not care as much about my flaws as somebody else might." The important thing is that everything fits together.

It's partly because storage strengthens the whole grid that it has found broad political support. Energy-storage technologies "are neutral as to the fuel source," Leah Stokes, a political scientist at the University of California, Santa Barbara, told me. They "can store any kind of power—clean or dirty." Storage may become a partisan issue if it begins clearly helping renewable energy to threaten fossil fuels. "The politicization of climate and energy policy comes from fossil-fuel companies that give enormous amounts to the Republican Party," Stokes said. "This is not some kind of ideological cleavage. It's fundamentally a material issue." For the time being, storage policy exists in what Stokes calls the "fog of enactment," where technologies are so new that we can't yet identify their greatest beneficiaries. Inevitably, there will be some losers, even if as a society—and a planet—we come out ahead.

The grid as a whole may never be perfected. We may never be able to get away from technologies with undesirable by-products; we may always rely in part on fossil fuels and nuclear power, backed up by Li-ion batteries and natural-gas "peaker" plants, used at times of high demand. But it's equally possible to envision a future in which some of the technology works out, and the globe is reshaped by a combination of renewable energy and renewable storage. In such a world, wind turbines and solar farms will spread over fields and coastlines, while geothermal plants draw power from below. Meanwhile, in caves and tanks, hydrogen and compressed air will flow back and forth. In industrial areas, energy warehouses will thrum with the movement of mass. In rural places, water will be driven belowground and then will gush back up. When the sun comes out and the wind rises, the grid will inhale, and electricity will get saved. During the doldrums, the grid will exhale, driving energy to factories, homes, offices, and devices. Instead of burning dead things, in the form of fossil fuels, we'll create and store energy dynamically, in a living system.

When I got back from Switzerland, I took a walk. The sun warmed my face, and I blinked in the breeze. Twenty years ago, it seemed inconceivable to many people that sunlight and wind could provide enough energy to meet our needs. Slowly, our intuitions shifted to accommodate renewable energy. A similar revision could come for renewable storage. Looking up, I saw clouds hanging in the sky, on the verge of rain; they were a bank of potential energy. Below my feet, I imagined the ground dipping ever so slightly under the city's weight, ready to spring back. Nature can help us generate power. Maybe it can help us hold on to it, too. ♦