Making Renewable Energy Practical

Few things get our attention more quickly than a loss of electric power. Many of our activities cease the instant energy from a generator many miles away stops supplying the electricity to light our homes or businesses, run our computers, lift our elevators, operate the industrial machinery on which our food supply depends, and countless other labor-saving tasks. While just a slap in the face at first, after a few hours, as food begins to spoil, sewage begins to accumulate, and night closes in, the inconvenience moves toward the potentially dangerous. Why can't our utility companies do something to prevent outages?

Unlike our water supply, which is often stored in elevated tanks that can supply us for hours or days, or our food supply in the pantry, electricity is used at the moment it is generated. But why can't large amounts of electricity be stored in batteries or through other means? And why couldn't this stored energy be used to make practical the large-scale use of wind or solar power, which don't generate energy when the wind is not blowing or the sun is not shining?

Batteries

A power plant generates alternating current (AC) where the plus and minus poles change 60 times per second — the reason behind the 60 Hz you see on all appliances. Batteries are direct current (DC) devices that produce energy continuously between the positive and negative poles with no alternation. Providing DC to an AC motor — everything from your air conditioner to an electric razor — would provide lots of smoke, but no rotation. To store AC energy in batteries, it must first be "rectified" to DC. Then when AC is required, the DC is converted to AC using an "inverter" that chops up the electric current, polarizes it, and reconstructs it into the semblance of an AC sine waveform.

Second, the number of batteries needed to provide storage for the output of a typical 1,000 megawatt (MW) power plant — one million kilowatt hours (kWh) each hour — would be incredible. A typical 12-volt automotive battery is rated at 70 amp-hours, which means it should deliver 70 amps at 12 volts for an hour. Watt-wise, this is equal to 840 Wh or 0.84 kWh. A simple calculation shows it would take 1,200,000 automotive batteries to store the power required to replace an hour of electrical production by the 1,000 MW plant. Of course, to have a reasonable lead-acid battery life, the batteries should never be discharged over 50 percent. Then there are the conversion losses from rectifying AC power to DC power and back again. Taking this into account, storing an hour's production from a 1,000 MW plant would require about 3,750,000 batteries, containing 75,000,000 pounds of lead. On three-foot centers, this would require a field of batteries covering more than a square mile — about 774 acres. And remember, this is for one hour's worth of electrical energy from a typical 1,000 MW nuclear or coal-fired power plant.

But why talk about storing power from conventional power plants to alleviate once-in-a-blue-moon power outages? Of more practical interest would be to determine the requirements to store energy from a wind or solar farm so that we could eliminate a conventional power plant altogether. Because wind and solar *always* need to be backed up against outages — owing to windless days of high pressure or clouds and precipitation — we assume that we need at least a two-day storage period. To use batteries to store enough wind power to generate something approaching reliable wind power equivalent to a 1,000 MW power plant would require 180,000,000 batteries covering about 58 square miles. This is in addition to approximately 2,000 well-sited wind turbines situated on something over 490 square miles. Keep in mind that these are not the windmills used by Farmer Jones to pump water for his cattle, but 1.5 MW behemoths with blades reaching up over 30 stories. The capacity factors are generously assumed to be 30-35 percent. The combined space for windmills and batteries would be just over half the land area of Rhode Island. Sometimes really good ideas have insurmountable troubles when real-world numbers are applied.

Lead-acid batteries obviously won't cut it, but would something else? There are, after all, many ways to store energy. (My least favorite is in fatty tissue.) They include chemical, electrical, thermal, kinetic, and potential energy storage methods. Since the prize for a workable method for large-scale electric storage (upon which any future, realistic wind and solar technology are totally dependent) is so great, this has been a major area of research by scientists for decades.

Chemical

As shown by the above analysis, batteries are not going to do the trick, not even battery technologies with somewhat higher energy densities than lead-acid, such as NiCd (nickel cadmium), NiMH (nickel metal hydride), and the lithium ion batteries used in your laptop. You can be sure that these are so expensive that they will never be even considered for major energy storage.

A second chemical possibility is the use of electrolysis to separate or dis-associate the hydrogen and oxygen atoms found in water — a process that always takes more energy than can be reclaimed from the process' end product, hydrogen fuel. A fuel cell could then be used to convert the chemical energy of hydrogen to create electricity directly. While having the desirable property of only producing water as an exhaust product, the conversion to electric power is only about 50-percent efficient, with the remaining 50 percent lost as heat. When the energy lost in production is considered, an overall efficiency of about 25 percent is possible when the hydrogen is stored as a pressurized gas, and about 20 percent when stored as a cryogenic liquid. Though no large-scale fuel cells exist, the Department of Energy gives a cost of $4,500 per kilowatt, which translates into $4.5 billion for fuel cells large enough to generate the electricity equivalent to a 1,000 MW power plant. (This price does not include transformers, buildings, hydrogen generation and storage, and the other apparatus required for a large power plant.)

Instead of recombining the dis-associated hydrogen and oxygen atoms, the hydrogen created by our electrochemical generator could also be burned to drive a conventional generator, just as we now burn natural gas to drive a steam turbine generator. But this isn't so good either. Basic thermodynamics show a loss of 65 percent of our energy to waste heat in the process. When considered from the standpoint of wind farms, which struggle to obtain a 30-percent capacity factor, the loss of some 75 to 80 percent of precious electric output to storage waste might be discouraging.

Electrical

The super or ultra capacitor is making a move and is an up-and-comer. A capacitor (of which there are likely thousands in electronic devices within a few feet of you) consists of "plates" that have opposite electrical charges and are separated by a dielectric or insulator. Energy is stored by the voltage potential between the plates. The advantages of the super capacitor are much faster charging times, a claimed weight reduction of 90 percent over lead-acid batteries, and no degradation for millions of recharge cycles. While possibly a boon for electric vehicles, we're still talking about 18,000 400-pound super capacitors to store *one hour's* energy from a 1,000 MW power plant. Multiply that by 48 for a wind farm's backup.

Another interesting concept in energy storage is the use of a superconducting magnet. At very low temperatures, the electrical resistance of certain elements and alloys is so low that it is immeasurable with current technology. An alloy of thallium, barium, and copper oxide is superconductive up to -234°F, far above the temperature of liquid nitrogen (-320°F.) So why don't we put the entire generated ampere of a power plant into an electromagnetic coil at a temperature below -234°F? Oops, I forgot to mention there is a *critical magnetic field* above which superconductivity ceases. It is estimated that any superconducting magnetic energy storage capable of storing an hour's output of a 1,000 MW plant would require a cryogenic loop of about 100 miles. We can extrapolate the cost of such a device to be about $20 billion in 2008 dollars, based on the similar Superconducting Super Collider program (cancelled in 1993 because of its price tag) with its 54-mile loop. Remember, that's for an hour's energy storage.

Thermal

Fireplaces continue to radiate heat long after the flames have died down because of the energy stored in the firebricks and other heated objects. Such thermal storage has been suggested by solar-energy advocates in order to maintain a constant kilowatt output by driving turbines from heat stored in molten salt.

Engineers at Sandia National Laboratory have designed just such a system. A mixture of sodium nitrate and potassium nitrate is melted (430°F) and heated to 1050°F by banks of mirrors focused on a "receiver," converting the solar energy into thermal energy. The molten salt then is used to generate steam that drives an electrical generator. The salt then flows to a "cold storage" tank where it is held at 550°F. This provides for a ride-through period when the sun isn't shining.

The design of the system is said to allow 200 MW of back-up generation for four hours — certainly an engineering feat of note. But because solar and wind generation operate at roughly 15 to 30 percent capacity factors and thus are forever struggling to be reliable sources of power, they just don't have spare capacity that needs to be stored except for momentary ride-throughs. If, as has been suggested in *Scientific American*, solar plants were vastly overbuilt to provide excess power generation, there would still be the problem of having the only reasonable solar sites in the United States located some 2,000 miles from the highly populated northeast section of the country. In reality, thermal-storage techniques would be better employed to level out the loads on nuclear and coal-fired "base load" power plants that often have excess capacity at nights or weekends.

Sandia engineers calculated that storing the heat to produce 800 Megawatt-hours of electricity would require two molten salt tanks, 30 feet high by 80 feet in diameter, using one for cold and the other for hot salt storage. For solar thermal storage needed for two days of backup to allow the possibility of eliminating a nuclear or coal-fired plant, 60 times this thermal storage capacity would be required — with provisions to ensure that this molten salt is never allowed to cool too much, whereby 210,000 tons of molten salt would turn into some very large bricks.

Kinetic

The energy in a linearly moving object is proportional to its mass times the square of its velocity. Though no one has suggested using the energy of a speeding freight train to store electrical energy, the kinetic energy flywheel has interesting possibilities — at least for small-scale storage.

The flywheel energy is a function of its mass, the square of the rotational velocity, and a constant known as the "moment of inertia." This constant takes into consideration the shape of the flywheel, e.g., a bicycle wheel, a solid cylinder like the Flintstones' stone tires, or many other possibilities. Let's look at the Flintstone-type cylinder, only made of steel. If its mass were 1,320 pounds in an 18-inch cylinder and it was spinning at 30,000 rpm, the flywheel would store about 26 kWh of energy. At that rate of rotation, the speed of the Flintstone mobile would be 1,875 miles per hour; consequently such high rotational speeds would need to be done in a vacuum with magnetic bearings. Storage capacity can be increased by increasing the mass or the rotational velocity, but in either case you run into the limiting problem of increased centrifugal forces that eventually lead to mechanical failure and destruction. To store just one hour's output from a 1,000 MW power plant would necessitate 38,500 flywheels of the type described above.

Potential Energy

A horsepower is defined as 550 foot-pounds per second, i.e., the energy required to raise 550 pounds one foot in one second. Except for inevitable losses, this process is reversible. In other words, the energy stored in a 550-pound weight hanging one foot above its resting position has the "potential" to provide one horsepower for a period of one second.

In theory we could store energy by raising large weights up and converting the potential energy back into kinetic energy when they are allowed to "fall" back to Earth. Assume we built a device that would lift 100 of these 550-pound weights and raise them to the height of a 10-story building. How much potential energy would we have? About 21 kWh. For a single hour's output of a 1,000 MW plant we would need 48,000 of these contraptions. But wait, all is not lost.

We could use water as our weight in something called "pumped storage." A reversible turbine-pump could raise water from one reservoir to another when a generating plant has extra capacity, and then release the water back through the turbine to generate electricity during peak demands. Pumping a liquid has vast advantages over raising 550-pound blocks. For a real-life example, we need only turn to the TVA's Raccoon Mountain Pumped Storage Plant near Chattanooga, Tennessee. Here water is pumped into a 528-acre reservoir 990 feet above the turbine generators. The 36,340 acre-feet of water in the upper reservoir is equal to 1.8 *million* 550-pound blocks and can sustain generating 1,600 MW for 22 hours!

Always looking for a way to compensate for the intermittent nature of wind power, European soft-energy advocates have proposed using pumped storage to make wind more reliable, yet the summary of a June 2004 Power Engineering Society report entitled *Sustainable Electrical Energy Supply With Wind and Pumped Storage — A Realistic Long-term Strategy or Utopia?* states:

> With recent data from one of the four control areas in Germany it is discussed how a sustainable energy supply based on off-shore wind power and pumped storage, called a "wind and water"-model, might look. It turns out that such an energy scheme, while feasible in principle, would require an immense storage capacity which would be impossible to realize. Thermal generation continues to be needed.

The problem with pumped storage? Look around. How many places do you see where there are two large reservoirs of water separated by 900 vertical feet?

Water or pumped storage won't work if only because of unfortunate world topography, but what about compressed air energy storage (CAES)? Pumping air into a tank obviously is a way to store energy. So why not pump air into a cavern (created by "hydro-mining" a salt formation) up to a pressure of 1,100 pounds per square inch and then release it to spin a turbine? That's what the first U.S. CAES plant in McIntosh, Alabama, has been doing for 11 years. Well almost. As with so many great ideas, there are devils in those details. When air is compressed, it must be cooled or the efficiency of compression drops off rapidly. And when it is expanded it is very cold and doesn't provide an adequate medium for driving a turbine-generator directly. So instead of running the turbine from the compressed air alone, the compressed air is blended with natural gas and the resultant high-pressure mixture is used as fuel. Such a plant requires about 50 percent of the natural gas that would be needed by a natural gas-fired power plant. Rather surprisingly, this plant was not intended to "store energy" as compressed air at all, but rather to boost the efficiency of a natural-gas turbine generating plant.

A second plant based on these same principles is being designed in Iowa. The present plan for this plant is to use it partially as a dumping ground for up to 150 MW of wind energy. But wind turbines provide power far below stated capacity factors (less than 30 percent), and they are not intended to "power" the plant, only to replace some of the natural gas that would be used to cool and compress the air. This means the wind turbines are likely close to useless because the grid already has enough base load during periods of low electric use (such as at night) to be able to reject wind generation. By itself, this plant would likely be a highly efficient gas-turbine generating plant for peak electricity usage periods. Excess capacity from conventional "base load" plants would be used to run the compressors during periods of low electric usage. However, with the wind-power faithful and the Energy Department involved with subsidies and credits, it may be difficult to determine the actual value of this technology.

And so …

While there are many clever and interesting ways to store energy, most of these are what the late Petr Beckmann termed as "piddle power" — not sufficiently robust and reliable to sustain an industrial economy. A noteworthy exception to this is "pumped storage" that is limited mainly to locations with large reservoirs vertically separated by hundreds of feet. Looking way out, the super capacitor is peeking up over the horizon and may be the device that changes the way energy is stored by our utility companies and in future electric vehicles.

Photo: Tennessee Valley Authority