Energy Storage

Howard C. Hayden, Ph.D.

A colleague at the University of Connecticut was a first-generation American, a descendent of Russians. He jogged on a regular basis but was a bit portly. His comment on his girth was, "Comes the famine, you skinny guys will be dying off like flies." Would that his wisdom were more widely understood.

This essay is not about bodily energy storage, but instead about energy storage as it relates to electricity. At all times, the power put into the grid is equal to the power consumed by users. The grid—transmission lines, distribution lines, and transformers—is a just-in-time delivery system that has no storage. What is the role of energy storage to this system that delivers electricity to our homes, businesses, factories, and hospitals?

Medical professionals have training in physical sciences that members of other professions do not often have and can help educate the public about the issues raised herein.

The Texas Big Freeze

A very good place to start is the recent problems with the electricity grid in Texas operated by the Electric Reliability Council of Texas (ERCOT), about which several facts have received wide press.

Wind turbine blades were covered with ice, rendering the machines useless. They were not winterized, in the sense that the blades did not have heaters to melt ice. Natural gas lines froze. Natural gas, of course, does not freeze at those temperatures, but impurities (including water vapor) did freeze at the non-winterized wellheads. Natural gas pumps, historically powered by engines using natural gas, have been replaced by electric pumps powered by power plants far away, including wind turbines.

Coal-fired power plants have been shut off by the government's war on coal and by price competition from cheap natural gas and highly subsidized wind and solar. There is a never-ending war against nuclear power, which is the planet's safest and most reliable energy source.

Among those energy sources listed, only two have on-site energy storage: coal and nuclear.

For wind, the only thing resembling storage is in the rotational energy of the spinning blades, and that energy is trivially tiny compared to energy demands on the grid. Likewise, solar energy depends on optical clarity of the sky and the angle of the sun's rays against the flat panels.

There is no incentive in ERCOT—or in any other Regional Transmission Organization (RTO)—for reliability. Nobody gets paid extra to have stored energy readily available. Moreover, within any given RTO, there is anything but a free market. Wind and solar can bid low (because of the subsidies) but receive payment at the going commercial rate instead of what they bid. I refer readers to Meredith Angwin's book *Shorting the Grid* for more of that story.

In the Texas debacle, solar power was just gone. Defenders of wind claim, correctly, that wind power was a small fraction of power on the grid even before the freeze hit. That defense, however, proves the point that wind power does not respond to demand, but rather to the vagaries of wind, and can be absent for protracted periods.

As the disaster proved, there was very insufficient on-site energy storage that could be called upon to provide power.

Some Energy Storage Schemes

We can store energy, but we can't store power any more than we can store velocity. Power, by definition, is the rate of conversion of energy from one form to another, such as the conversion of steam heat into kinetic energy of a moving steam locomotive or steamship, or the kinetic energy of wind into the gravitational energy of water raised up from a well. That is: *power = energy divided by time*, and alternatively, *energy = power times time*. A generic plot of power versus time shows the amount of power represented by the distance along the vertical axis, and time on the horizontal axis. For a given time interval, the energy delivered is the area under the curve, the accumulating product of *power times time* (Figure 1).

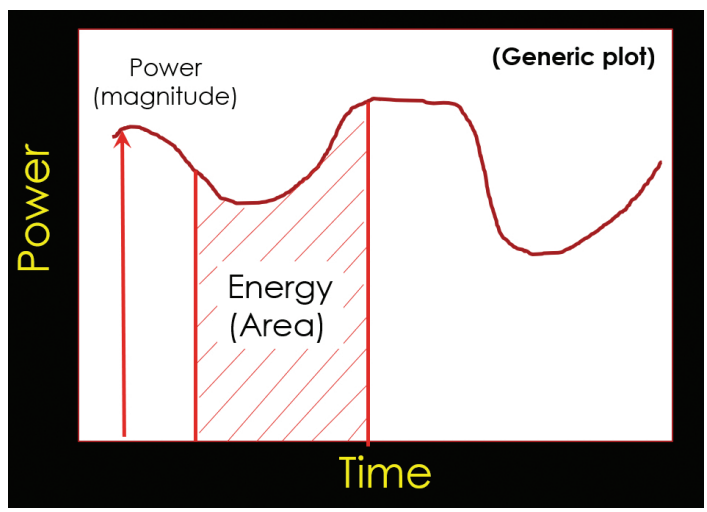

Figure 1. Power and Energy

Hydroelectric power plants rely on the gravitational energy of the water stored behind the dam. The amount of power is proportional to both the drop in elevation and the flow rate of the water. In some topologically favorable places, utilities use pumped-hydro schemes to store energy. When excess power is available from their conventional power plants, it is used to pump water uphill to be stored behind a dam, and the energy

is retrieved in the afternoon to supplement the grid power.

Of course, some energy is lost in both processes—storage and retrieval. In the US, pumped-hydro contains a total of about 25 GW, versus an average consumption of 475 GW, and experiences a net energy loss of 5-10 billion kilowatt-hours (kWh) per year. Despite the net loss of energy, the storage system lets the rest of the grid work at a steady pace, thereby increasing efficiency.

In addition to pumped-hydro, other storage schemes involve batteries, flywheels, hydrogen, compressed air, molten salt, and capacitors, all of which have some current uses. Round-trip efficiencies vary depending upon technologies, but all involve energy losses. It is not my purpose here to pick winners and losers, but rather to evaluate the amount of storage, rather than the type of storage.

Storage for Renewable Energy

Advocates for renewable energy like to refer to "solar, wind, and other" renewable sources, or to "renewable sources, such as wind and solar," avoiding the discussion of what those "other" renewable source might be.

A common mantra is that energy from solar and wind is now cheaper than energy from conventional power plants. That questionable claim involves more politics than science, but we are free to ask whether you can buy one kWh of midnight solar energy for $1 million dollars. (For a reference point, when I first learned about foot-pounds, horsepower, watts, kilowatts, and kilowatt-hours back in junior high school, the price of electricity was about 4 cents per kWh, and a candy bar was a nickel. Now, I pay about 14 cents per kWh, and have to take out a loan to buy a candy bar.) The only way to (pretend to) get midnight solar electricity is to store solar energy when the sun is shining, and to release it at midnight.

When the electrical grid is 99.9% reliable, you can count on a lack of power for a total of almost nine hours per year. If the reliability is 99.99%, you are still without power for the better part of an hour per year. For some people and businesses, the lack or power is a mere inconvenience. For some round-the-clock industries, such interruptions are very expensive, so they must have on-site generation ready to go at a moment's notice. For hospitals, with some people on life-support, many others on around-the-clock electronic monitors, some people in surgery, active HEPA filtering, and so forth, power cut-offs can be a matter of life and death.

For the electrical grid, solar and wind are basically worthless without real-time stabilization from conventional power sources and/or massive storage. At present, wind and solar are supplementary, but many enthusiasts and politicians are pressing for 100% renewable energy by (pick your date). Others are pressing for 100% "carbon-free energy" by (pick your date). Prestigious medical publications advocate without reservation for renewable energy, which is "expected to increasingly supplant the traditional fossil fuel energy industries of coal, oil, and natural gas."[1]

Solar

On a year-round basis, the average power produced by solar panels is 15% to 20% of what they say on their nameplates. In technical terms, the *annual capacity factor* is 15%-20%. Obviously, there are seasonal variations, but for sake of simplicity, we will assume 16.7% (= 1/6), and assume that a huge array of solar panels produces full power four hours a day (between 10 am and 2 pm), and nothing at other times. We will apply this model to a summer day in California for which we have a power curve[2] and assume that every day is equally sunny.

As shown in Figure 2, the average daily power demand is about 35 GW, and the solar system that supplies the energy must supply not only the 35 MW to handle the load during those four hours, but also must send an additional 700 GWh during that time to the storage system to handle the 24-hour 840-GWh demand.

From the standpoint of required power, the solar array must produce the 35 MW being demanded during the four-hour time of sunlight but must also supply an additional 175 GW to store the 700 GWh during that four-hour time frame. That is, it must be able to supply 210 GW.

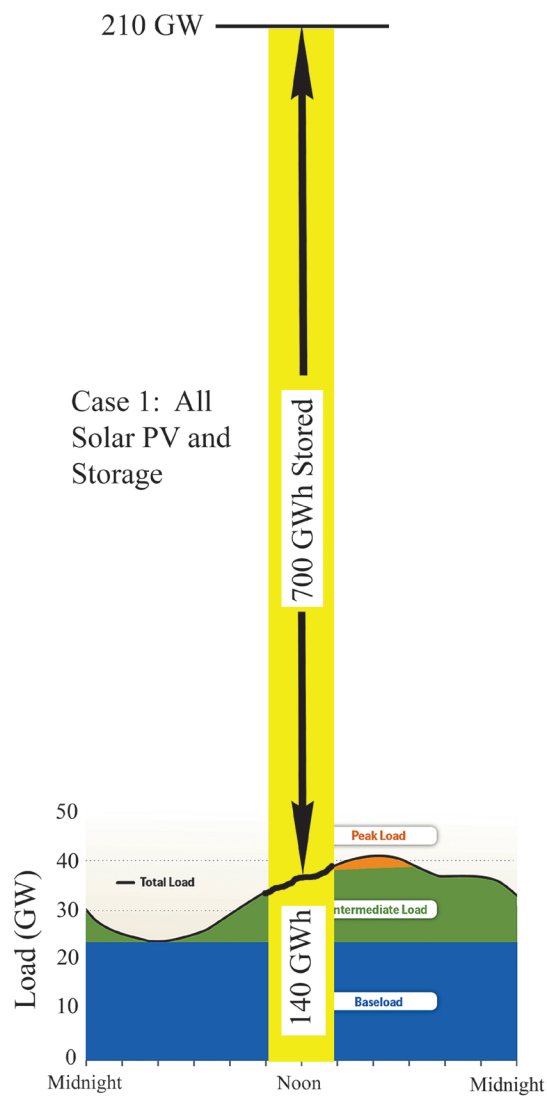

Figure 2. A Load Curve for a Summer Day (in 2009) in California. A hypothetical solar array provides all necessary energy with an average power demand of about 35 GWh (35,000 MWh).[2]

This simple model shows us that the solar array must provide six times as much power as is used on average, and the storage system must hold 20 hours' worth of one day's energy. We have assumed optimistically (delusionally) that every day is sunny, contrary to all our experience. The Arctic blast that hit Texas lasted for days. People in northern states can go for weeks without bright sunlight. Remember, the idea is to have a grid that delivers power with 99.9% or better reliability.

Wind

The annual capacity factor for wind these days is 35% *by design*. In the Carter era, it was 20%. To explain the design concept, let us address two ridiculous designs. In the first, we attach a 1-MW generator to a pinwheel. The power production will be zero, and so will the capacity factor. In the second, we attach a huge rotor (say 50 meters in diameter) to a 1-watt generator. This design is capable of producing 1 watt every hour of the year, so its capacity factor will be 100%. That is, we can design for an annual capacity factor of any value we want between 0 and 100% by adjusting the relationship between generator capacity and rotor diameter. In the Carter era, the idea was to boast about the nameplate power, not effective output, so they opted for 20%. A better engineering design, from the standpoint of costs and output, is 35% capacity factor.

For our simplified wind-power model, we assume full power for eight hours (33% of the day) and no power otherwise.

As shown in Figure 3, the wind system has to produce 104 GW during those eight hours to provide the power demanded at the time and to store enough energy for the rest of the day. Again, the winds can be calm for days on end.

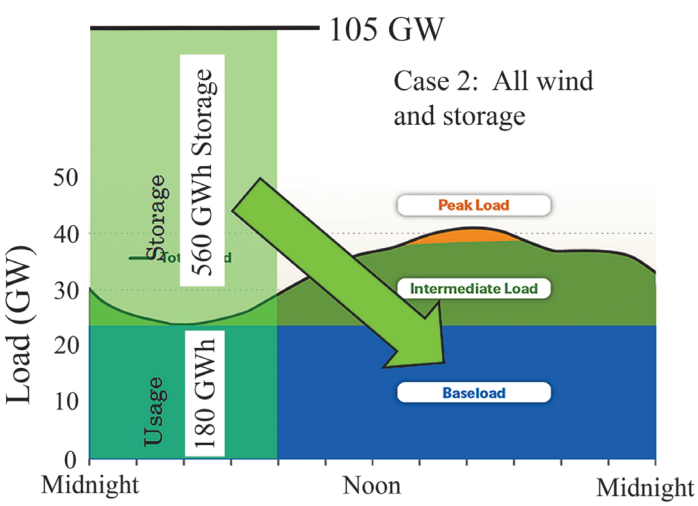

Figure 3. Handling California's Summer Load with Wind.

Absent reliable power from coal, natural gas, or nuclear, energy storage for solar and wind must be capable of handling many days' worth of energy. The power requirement for the solar system must be about 6 times the average demand just for a succession of sunny days, but 12 times the demand for a bright day followed by a cloudy day, 18 times average demand for a bright day followed by two cloudy days, and so on. With wind, divide those numbers by 2. In any case, both the power demand and the amount of energy storage are huge. In both cases, we have made the simplifying assumption that the efficiency of storage and that of retrieval are both 100%.

Some sites are obviously unsuitable because of low average wind speed (Table 1). Sites are characterized by classes according to the average wind power at 50 meters elevation above the ground.[3] (Terminology: in the case, the word *power* is taken to mean the kinetic energy of the air per unit time passing by a certain point. It is not the power converted to electricity at the location.)

Table 1. Classes of Wind Power Sites

nrel.gov/wind/pdfs/map_nwtc_wind_power.pdf

Wind Power @ 50m

Class	[W/m^2]
1	< 200
2	200 - 300
3	300 - 400
4	400 - 500
5	500 - 600
6	600 - 800
7	> 800

The power produced by a wind turbine follows basically the same curve for all manufacturers, because the physical phenomena that control the power are the same for all sites and machines.

Figure 4 shows two curves plotted against wind speed. The black line shows the percentage of full power, be it a 1-MW machine or a 5-MW machine. At low wind speed, the machine doesn't turn fast enough to generate electricity. Adequate gearing would presumably make it possible, but there is so little power available in the wind that the effort would be pointless. Between about 4 meters per second and about 12 m/s, the power output follows the velocity-cubed law (with an efficiency rising from 25% to 40% over that range, and then tails off to 100% of full power. In the full-power range, the blades are rotated on their own axis ("trimmed," in aeronautical terms) until they reach full feather at 25 m/s, at which point the turbine is shut down to keep it from destroying itself.

An equation called the Rayleigh Distribution described the general nature of wind speed, and is graphed in Figure 4 for a class-6—"Outstanding"—site. At this type of site, more than half the time the wind turbine produces less than one-half of full power. Full power is achieved only 11% of the time.

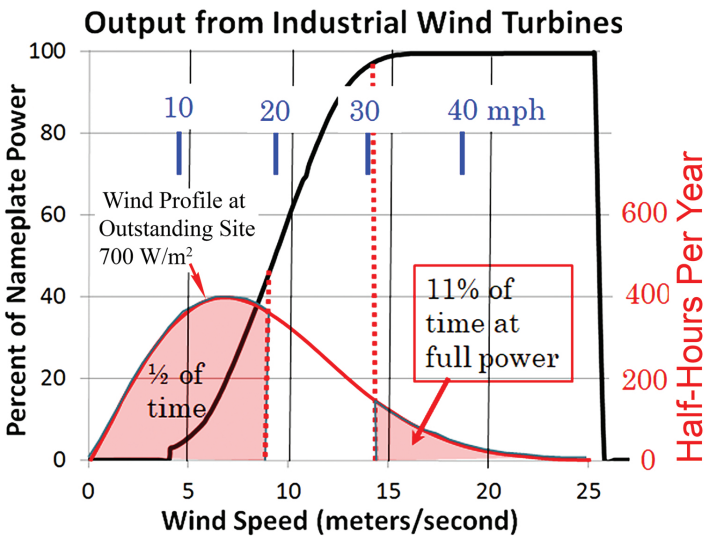

Figure 4. The Power Curve for an Industrial Wind Turbine, with the Wind Profile of a Class-6 Site Superimposed.

Enhanced Baseload

Now let us consider a better use of storage. In the case of summer days in California, the average power consumption is 35 GW, but the baseload power is around 24 GW. Imagine increasing the power from those coal plants, nuclear plants, and natural-gas combined-cycle workhorses by roughly 50% to equal the 35 GW average demand. During the times of low demand, the excess power goes into a storage system for use during times of higher demand (Figure 5).

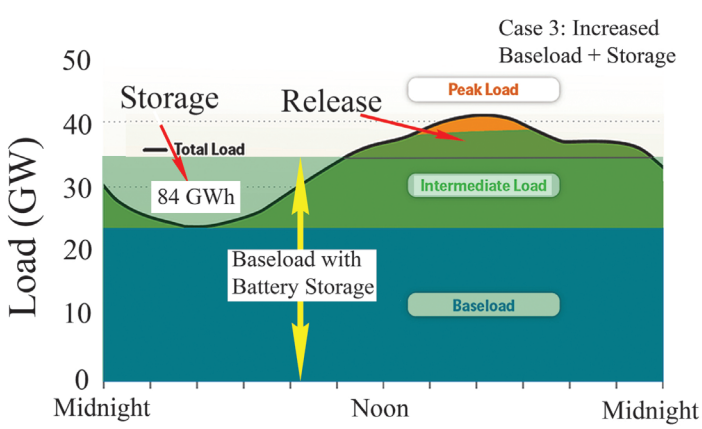

Figure 5. Conventional Power Supplying Baseload Is Increased Enough to Equal Average Power Demand.

In this case, the amount of power required is a mere 50% greater than the baseload stations provide currently, and the amount of energy to be stored is about 25% of *one* day's energy.

The Wind Is Blowing *Somewhere*

Some enthusiasts for renewable energy may argue that the wind is always blowing *somewhere*, so all we need is the ability to transmit that power to where it is required.

The longer the transmission line, the more heat is lost to the resistance in the wires. To compensate, utilities use transformers to increase the voltage and thereby decrease the current in the lines. A factor of 100 increase in voltage cuts the power loss per mile by a factor of 10,000. A typical transmission line voltage is 345,000 volts. Very long distances require higher voltages, and most of the power loss becomes radiation losses from those super-long antennas, so utilities will convert to DC (at perhaps a million volts) to reduce the radiation losses.

In the U.S. as a whole, the power loss in transmission and distribution is 6.2% of the generated power, largely because most electricity is produced within 100 miles of where it is used. Clearly, the losses would increase if New York's electricity all came from West Texas.

What happens when the air is calm in West Texas? Maybe it is blowing in Wyoming, Alabama, or Northern Minnesota. Each of those places must therefore have enough power to run the entire grid; alternatively, each location must have its own adequate storage to ride out the times when power is not available.

Storage Systems

Through 2017 the installed battery power in the U.S. is roughly 300 MW, and the total energy capacity of all installed battery systems is less than 1,000 MWh,[4] as shown in Figure 6. By comparison, a single nuclear power plant typically produces 1,200 MW around the clock, and will produce around 20,000,000 MWh between refueling times.

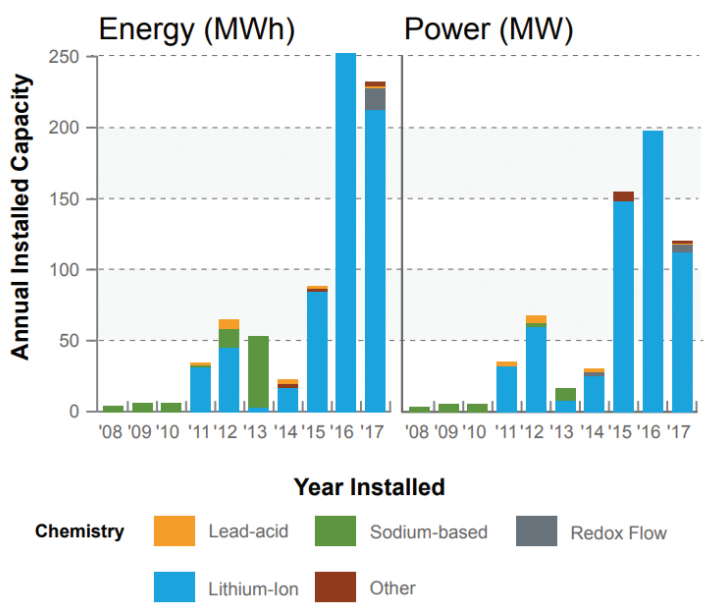

Figure 6. Installed Battery Energy Capacity (MWh) and Power Capacity (MW) by Year.[4]

Lithium is a very desirable material to use for batteries for two reasons. It is the lightest metal, and for transportation purposes, lighter is better. It is also the most electro-negative metal, making it the best from the standpoint of energy. It is

therefore the most common material for large-scale batteries, as shown in Figure 6. Lithium is far less common than sodium, and I (as a non-chemist) suspect that sodium will eventually find a lot of use in stationary-battery applications.

Energy is lost during both storing and retrieving energy. In the case of batteries, there is a nominal *open-circuit voltage* (OCV) that exists when the battery is idle. To charge the battery requires the voltage to be higher than the OCV, and more so for faster charging. When the battery is used to supply power, the voltage is lower than the OCV, and more so the faster the charge is withdrawn from the battery. In Figure 7, the energy loss during one charge/discharge cycle is represented by the hatched area.

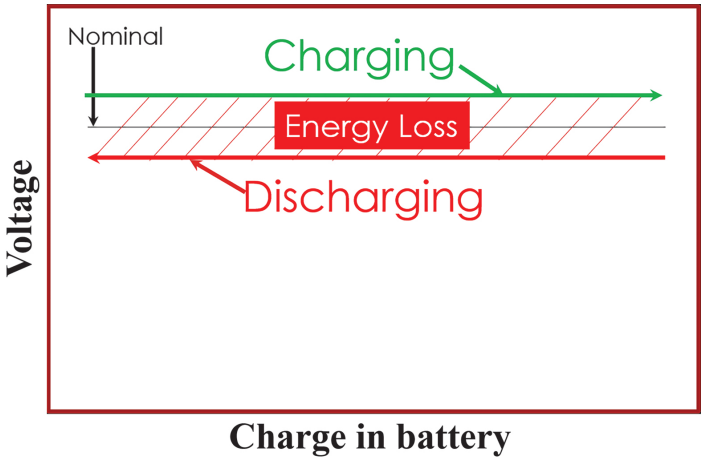

Figure 7. Energy Lost in Discharging a Battery.

Hydrogen is often considered as a good storage medium. Hydrogen can be produced by running a current through water, and burning hydrogen produces water as a by-product. However, when you buy a tank of hydrogen, the gas most likely came from natural gas, because it is cheaper. Hydrolysis does work and works well, but of course you get out less energy than you put in. The maximum attainable efficiency for electrolysis is 83%, and the maximum attainable efficiency for producing electricity in a fuel cell is about 65%, resulting in a maximum of 54% round-trip efficiency.

There is also the problem of storing hydrogen. It takes energy to pump in into a high-pressure tank, and it takes energy to cool it down to liquid-hydrogen temperature, and to keep it cold. There are some exotic ways to store hydrogen interstitially in some materials for example, but they are very materials-intensive.

Conclusions

Enthusiasts for solar, wind., and unspecified "other" renewable energy have vastly underestimated the amount of (a) generating power, (b) storage power, (c) storage energy, and (d) grid capacity that would be required for their 100%-renewable-energy scenario. Renewables are a skin-and-bones occasional helper, not a robust employee.

One has only to ask: (a) what are the year-round capacity factors are for the devices; (b) how many days' storage is required to achieve in excess of 99.9% reliability; and (c) how much power would be required to store that energy. By any measure, it is vastly better to use storage for conventional power than for unreliable solar and wind.

Howard Hayden, Ph.D., is an emeritus professor of physics from the University of Connecticut. Contact: corkhayden@comcast.net.

REFERENCES

1. Sumner SA, Layde PM. Expansion of renewable energy industries and implications for occupational health. *JAMA* 2009;302(7):787-789. doi:10.1001/jama.2009.1214.
2. National Renewable Energy Laboratory. Solar Power and the Electric Grid. NRE Energy Analysis. NREL/FS-6A2-45653; March 2010. Available at: https://www.nrel.gov/docs/fy10osti/45653.pdf. Accessed May 5, 2021.
3. NREL. Classes of wind power density. *Wind Energy Resource Atlas of the United States*; 2005. Available at: https://www.nrc.gov/docs/ML0720/ML072040340.pdf. Accessed May 5, 2021.
4. Bowen T, Chernyakhovskiy I, Denholm P. Grid-scale battery storage: frequently asked questions. National Renewable Energy Laboratory; n.d. Available at: https://www.nrel.gov/docs/fy19osti/74426.pdf, Accessed May 5, 2021.