Mixing water and electricity: Thermal energy storage as a microgrid component

Edward "Ted" Borer, PE, Energy Plant Director, Princeton University

"Why don't you have batteries in your microgrid yet?" "Do you have them on order?" "You need batteries to go with all that solar PV, right?" A lot of people are asking questions like these, assuming batteries are the only method of storing electricity. As we add more and more renewable generation, most of us are painfully aware of the challenges that renewables present, chiefly the mismatch between electricity supply and customer demand. But batteries aren't the only answer.

THE DISCONNECT BETWEEN RENEWABLE GENERATION AND DEMAND

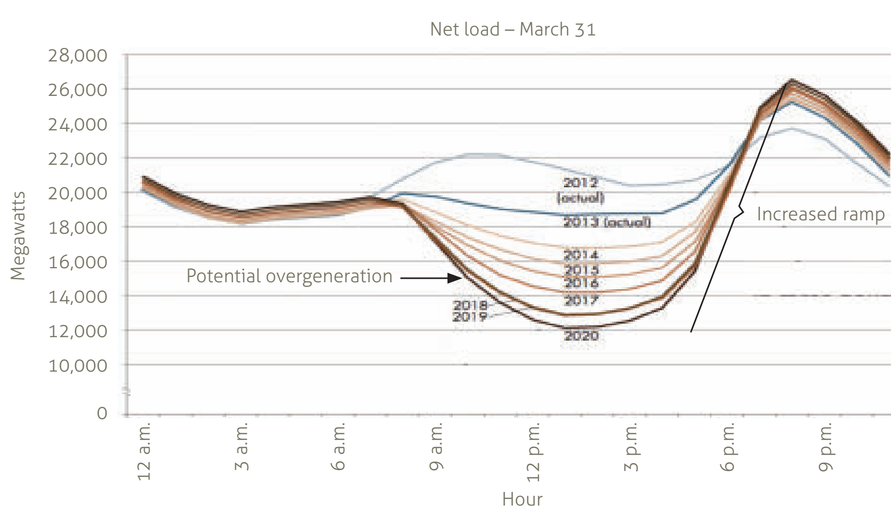
At the risk of stating the obvious, we all know that solar power generation peaks each day around noon and drops off steeply toward sundown, contributing nothing after dark. Unfortunately, a community's use of electricity does not peak at noon or disappear at night. More typically, electric demand peaks between 5 p.m. and 7 p.m., when workplace demand is still high but many people have returned home and added residential HVAC, lighting and cooking loads.

The combination of rapidly decreasing solar power generation with increasing electric demands results in an extremely steep ramp rate required from controllable generators, as illustrated in figure 1. Because of this, utilities cannot simply run their baseload plants (which are most efficient, most cost-effective and least polluting, but very inertial). Instead, they need to obtain a lot of the afternoon and evening electric energy from less-efficient, high-marginal-cost, more-polluting but highly responsive peaking plants. Baseload plants include natural gas combined-cycle plants, which can operate at greater than 60 percent efficiency, and nuclear energy plants. By contrast, peaking plants such as gas turbines and diesel generators often run in simple-cycle mode at less than 35 percent efficiency. Absent a reliable system of energy storage, increased production of renewable electricity will require greater use of these inefficient peaking plants.

INCREASING RENEWABLE GENERATION WITHOUT FEEDING THE DUCK

In simple terms, we want to smooth out the apparent demand for electricity at the microgrid edge or even shape

FIGURE 1. Example of a "duck curve" for a typical day, California Independent System Operator. Increasing deployment of solar energy is having a growing impact on the power grid, as illustrated here. The curve shows the net load on other grid resources as solar contributes to the grid during daytime, peaking in early afternoon and then dropping off as the sun sets. As solar penetration grows, this requires an increasing need for other generation sources to reduce output in the morning and then rapidly ramp up in the evening.



Source: U.S. Department of Energy, "Confronting the Duck Curve: How to Address Over-Generation of Solar Energy" (https://tinyurl.com/y8y2oarj).

our apparent demand to match renewable generation. For the most part, utilities can't see or control what is happening beyond their customers' meters at the point of interconnection. They know customers are using electricity but don't know what is being done with that electricity. Utilities can only control the combination of generators they use and perhaps store energy or discharge it as electricity on the grid. As microgrid designers, owners and operators, we have a lot more options.

WHAT DO CENTRAL ENERGY PLANTS AND ENERGY STORAGE DO?

Our district energy plants convert energy from one form to another. This invariably involves some inefficiency and energy loss. In power generation, we convert fuel energy to electricity using gas turbines, steam turbines and boilers. These each lose some energy in the form of heat. In a cooling plant we convert electric energy or steam energy into cooling potential by using chillers, heat pumps, geoexchange and cooling towers.

Energy storage does two basic things: It decouples the *time* of generation from the *time* of use, and it decouples the *rate* of generation from the *rate* of use. Energy storage is a tremendously powerful tool within a microgrid. But energy storage comes in a lot of flavors.

Batteries have their place. They are important and useful if you are using the stored energy to power nondeferrable activities like lighting, motors and computers. Batteries are also excellent at responding to rapid changes in demand. To date, however, battery technology costs more per kilowatt-hour and requires more real estate per kilowatt-hour than thermal energy storage. Battery technology involves higher maintenance and more exotic chemicals and materials than thermal storage; and batteries have much shorter operating lives than simple concrete or steel tanks full of water.

Thermal storage is, in fact, one of two basic strategies that are more cost-effective than battery energy storage for the electricity customer.

First, we can change the time of *deferrable* electric energy demands. Today, retail consumers have no economic motivation to change behavior. Their electric rates are the same all day and all night. But if retail consumers were exposed to continuously variable electric rates, or even multitiered time-of-day rates, vast amounts of creativity would be applied to change the time of use for such things as dryers, dishwashers, water heaters, slow cookers and vehicle chargers. Even refrigerators and freezers could be precooled and then allowed to coast through daily demand spikes. These modifications could be done using straightforward application of inexpensive existing technology, creating incentives to change behavior just as some large industrial customers experience today. Many wholesale electric customers have time-of-day rates and capacity charges that are strong economic motivators to change the time of electric purchases, which helps ease the strain on the grid during peak periods.

Second, we can add thermal energy storage. Electric utilities don't fully appreciate how much of their product is not used for laptops or lighting. A lot of their product is used to heat something up or cool something down. Thermal storage is more energy-efficient and more space-efficient, has better round-trip efficiency, requires less exotic materials and has a far lower lifecycle cost. Proper applications of thermal storage in a microgrid can reduce system capital and operating costs, improve reliability, smooth demand profiles and reduce environmental impact.

EXPLAINING THERMAL ENERGY STORAGE TO NONTECHNICAL PEOPLE

Let's consider energy storage in a few real-world situations. Understanding these should help in your conversations with your customers and your boss.

An air conditioner

A bedroom air conditioner must operate at all times when there is a need for cooling. Its capacity must match or exceed the predicted demand. It may have a few stages to turn down, but primarily it modulates by turning on and off the compressor. These cycles can be audibly distracting and are stressful on the equipment. Peak electric demand is likely to match the machine's peak rating. Operation is heavily influenced by the room's solar heat gain and by its occupant's activities. So, a room air conditioner's peak demand is likely to be concurrent with peak demand elsewhere on the electric grid, and its use will add to the grid's peak.

Without a complete spare, there is no redundancy: The failure of one component will leave the user without cooling. It is only reasonable to add redundancy in increments of 100 percent. There is little opportunity to add effective thermal storage to this system other than increasing the room's own thermal mass (a form of energy storage). The individual air conditioner has a relatively low capacity factor, i.e., the sum of its equivalent full-load hours in an annual cycle is quite low. Since residential electric energy is typically sold at a fixed cost per kilowatt-hour and does not have a demand component, there is little economic motivation to add thermal storage … yet.

A district cooling system

Now we'll consider a district cooling system without thermal storage. It must operate cooling, pumping and heat rejection equipment at all times when there is a need for cooling. Peak equipment capacity must match or exceed the system's peak predicted demand. Equipment must run at an output level determined by the demand, not optimized at its optimal efficiency point. All equipment with moving parts and fluids or changing temperatures will eventually break down. This failure is somewhat more likely to happen on a "design day" since that is when the equipment is being pushed hardest and run under the most extreme and stressful conditions.

A district cooling system already has advantages over a room air conditioner, though. With multiple buildings, there will be diversity in the times of peak demand. Some building faces will be in shade

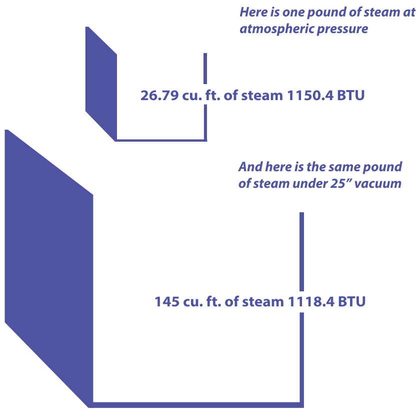
The Steam Heating Professionals

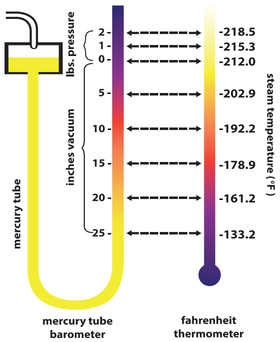
VariVac® (Variable Vacuum)

G.S. Dunham is your expert resource for engineers, facility managers, and decision makers for all your steam heating systems and equipment needs providing sales, service and support.

- Existing steam heated subscriber stations (any age) retrofitting to VariVac®.
- New construction - Hundreds of installations in NYC since 2001 and thousands of existing, operating buildings prior to 2001.

The VariVac® Sub-Atmospheric Steam Heating System has the ability to control the volume and temperature of steam for maximum tenant comfort with minimum wasted energy.





IT'S SIMPLE, STEAM IS THE MOST EFFICIENT.

CALL US!

Ask for Dominic

THE STEAM HEATING PROFESSIONALS
718-886-4232
GSDUNHAM.COM
SALES@GSDUNHAM.COM

MANUFACTURERS REPRESENTATIVE FOR: MEPCO, ELGE®, Vent-Rite®, VARI-VAC®

while others are in sunlight. Building programs and hours of occupancy may vary. With multiple occupants, the cooling demand curve will be more continuous and smoother, as not all building cooling loads will be concurrent. Multiple buildings have considerable thermal mass. In sum, they will heat and cool more gradually than any individual space.

So the total cooling equipment capacity does not have to be as large as the total of the individual space cooling needs. Fewer pieces of cooling equipment are required, and they can be larger and more efficient. Noise, aesthetic issues, space use, equipment operation and maintenance, and environmental impact can be centralized – along with the opportunity to manage each of these. Equipment capacity factors tend to be higher due to diversity in demand. With multiple machines, redundancy can be added to this system in increments of less than 100 percent, i.e., three chillers each rated at 50 percent of peak demand or five cooling tower cells each rated at 25 percent of peak demand. This allows each piece of equipment to operate closer to its peak efficiency level.

District cooling with thermal storage

When we add thermal storage to a district cooling system we gain additional benefits. We can minimize the cost of purchased power by purchasing at low-demand periods. We can reduce total energy use since equipment can be operated at its highest efficiency point under steady load. Heat is being rejected at lower nighttime wet-bulb temperatures, and there are reduced electric transmission losses in a lightly loaded power grid. A lower storage temperature can be used to increase the chilled-water differential temperature, thus lowering the total pumping energy required. Note that for overall system optimization, pumping energy savings must be balanced against a reduction in chiller efficiency.

Through careful management, thermal storage can be used to purchase electric power from the grid when the least-polluting combination of generators is in service and to avoid power purchase when the most-polluting generators are in service. It reduces the costs and system stresses associated with peak demands.

Thermal storage can increase reliability and ease of operation since production and storage take place prior to the moment of demand and continuous production is no longer needed. Thermal storage can be used to increase nighttime load and reduce daytime load. It allows more daytime maintenance and helps avoid unnecessary use of overtime work. Chilled-water thermal storage can have excellent low load performance (turndown) since a pump and variable-frequency drive can be controlled to a much lower level than an equivalent capacity chiller.

THERMAL STORAGE CAN BE USED TO PURCHASE ELECTRIC POWER FROM THE GRID WHEN THE LEAST-POLLUTING COMBINATION OF GENERATORS IS IN SERVICE.

A solar hot water system

Consider a family of six, which might consume 50,000-100,000 Btu in a one-hour period early in the morning as they are bathing and washing dishes. An efficient evacuated-tube solar collection system sized to meet this rate of energy demand could cost over $50,000 and still wouldn't work at night! If constructed, this system would have an extremely low capacity factor. Most of the day when no hot water was being used, its energy collection capability would be wasted, and most of its heat would have to be rejected back into the environment. Instead, we design a smaller collection system that harvests energy through the entire day, and we include thermal storage using a hot water tank so the energy can be concentrated and delivered in a much shorter period. This system would take less space and could be built for less than $10,000.

A field of potatoes

An even greater difference between the rates of energy storage and delivery exists in agriculture. Consider a field of potatoes where the solar energy input occurs over a period of months. The plants absorb solar energy, concentrate it and convert it to chemical energy through photosynthesis. The potatoes are harvested at one point in time. Then they are stored for some period. The energy delivery (consumption) occurs at one point in time. We can hardly imagine enjoying a dinner that could only be eaten at the rate plants convert sunlight! Energy storage is a necessary component of this system. Unlike cooling systems, cars and bicycles, the energy input to a solar heating system or a field of potatoes is not in our control; it is not usually concurrent with our need for energy; and the energy is often delivered at a lower rate than we want to use. We must take advantage of the sun's energy when it is offered to us regardless of when we want it. Again, by adding storage to these systems, we can decouple the time of production from the time of need.

A geothermal heat pump

A closed-loop geothermal heat pump uses a refrigeration cycle to draw heat energy from a building and store it in the ground in the summer when it is operating in cooling mode. Over a period of months the soil, water and rock around the geothermal well will be warmed above their natural temperature. There will be some conductive heat dissipation and some convective losses through water movement. But as they are warmed, the soil and rock store energy. The earth is being used as thermal storage. Then in the winter, the heat pump can be used to retrieve heat from the ground. This form of annual energy storage can be extremely efficient and often has coefficients of performance (ratio of energy delivered compared to the energy input) of greater than 4.0!

CONCEPTS AND CONCLUSIONS

Rates of energy production and use may be different. Times of energy production and use may be different. The cost and availability of energy is time-sensitive. Thermal storage allows us to decouple the time and rate of energy production from the time and rate of demand. It can be used to take advantage of low-cost electric power. It can be used to take advantage of solar energy. It can be used to add reliability, operate at best efficiency, smooth out a demand profile and deploy smaller equipment to meet peak demands. Adding energy storage can reduce first costs and often results in lower lifecycle costs than selecting production equipment for peak loads.

The price and emissions associated with power production are volatile and time-sensitive. Increasingly common time-of-day pricing will motivate all types of customers to move optional energy consumption (such as water heating, battery charging, dishwashing and laundry machine operation) to nonpeak hours. Residential time-of-day utility rates are needed to motivate "smart grid" technology on the residential scale. This will tend to smooth out grid demand, use more power from more efficient baseloaded plants and avoid power purchase from peaking plants. Utilities or grid operators will need to report time-of-day emissions rates for customers who have made carbon dioxide reduction commitments to fully optimize energy use and minimize net emissions.

By learning from examples as humble as potatoes, we can create reliable energy delivery systems that have a dramatic impact on our wallets as well as on the environment..

Edward "Ted" Borer, PE, *is the energy plant director for Princeton University and is actively involved in campus energy and carbon emissions reduction efforts. With over 30 years' experience in the power industry, starting in the nuclear industry in the early 1980s, Borer is a registered professional engineer with bachelor's and master's degrees in mechanical engineering as well as CEM, CEP and LEED AP certifications. He has leadership roles in IDEA and the New Jersey Higher Education Partnership for Sustainability and is a founding member of the Microgrid Resources Coalition. Borer has provided briefings for U.S. Senate members, FERC commissioners and state officials. Principal of consulting firm Borer Energy Engineering LLC, he speaks regularly on energy topics and has published numerous articles in trade magazines and peer-reviewed journals as well as a book chapter on combined heat and power. He may be reached at etborer@Princeton.edu.*