Explaining General Concepts About Thermal Storage

Edward T. Borer, PE, CEM, LEED^{AP}
Princeton University, Facilities Engineering

ABSTRACT

Proper applications of thermal storage can reduce system capital and operating costs, improve reliability, smooth demand profiles, and reduce environmental impact. Key concepts of energy storage are explained, using simple, familiar examples.

INTRODUCTION

It may sound like a bad joke… "What do a house of worship, a bicycle headlamp, an air conditioner, and a potato have in common?" In fact, they share quite a lot when it comes to the need for energy storage.

There are few people outside our professional community who understand the importance of thermal storage and its effect on a system's capital cost, operating cost, and carbon emissions. Even engineers who recall solving inductor-resistor-capacitor problems in school may have trouble explaining the real world impact of adding capacitance to a dynamic system. What does energy storage do? What value does it add? How do we communicate that to the lay person who may hold a project's purse strings?

Let's consider energy storage in a few real world situations. Understanding these should help in your conversations with customers. Note that these descriptions are necessarily simplified and generalized for clarity.

AN AIR CONDITIONER

A bedroom air conditioner must operate whenever 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 the compressor on and off. 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 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; i.e., the failure of one component will leave the user without cooling. It is only reasonable to add redundancy in increments of 100%. There is little opportunity to add effective thermal storage to this system other than increasing the room's own thermal mass. 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.

A DISTRICT COOLING SYSTEM

Now consider a district cooling system without thermal storage. It must operate cooling, pumping, and heat rejection equipment whenever 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 best 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 while others are in sunlight. Building programs and hours of occupancy vary. With multiple occupants, the cooling demand curve will be more continuous and smoother; i.e., not all building cooling loads will be concurrent. Multiple buildings have considerable thermal mass (a form of energy storage). 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%; i.e., three chillers, each rated at 50% of peak demand, or five cooling tower cells, each rated at 25% of peak demand.

CONTROLLING THE POWER GRID WITH AN ECONOMIC SIGNAL

Electric power is a highly volatile commodity that changes in price every few minutes. The price may vary by a factor of ten or more in a few hours. While residential customers pay a fixed price per kilowatt-hour, in a commercial and industrial electric tariff, there is usually a variable energy component based on the utility's marginal cost of production—at the time and location of delivery. This locational marginal price (LMP) varies in relation to the grid demand. In the middle of the night when demand is lowest, the LMP tends to be lowest. In the peak of a hot summer weekday when demand is highest, the LMP reaches its peak.

A load dispatcher may have dozens of generators available that could provide power to the grid. There may be hydro-electric dams, nuclear power plants, coal-fired plants, natural gas fired plants, gas turbines, and diesel generators, as well as solar photovoltaic arrays and wind turbines. Each plant will have a unique capital cost and "heat rate" (efficiency expressed as Btus of fuel per kilowatt-hour). These plants are spread over several hundred square miles, often in multiple states. How does the power grid operator decide which plants should run and then communicate that to each one in real time? Effectively, they hold an online commodity auction 24 hours a day. All generators throughout the grid may contribute power at any time, but they are only compensated at the rate offered by the load dispatcher at the time.

Imagine its 2:00 a.m. The grid demand is low. The LMP may be $0.03/kWh. This price will entice only a few generators to run.

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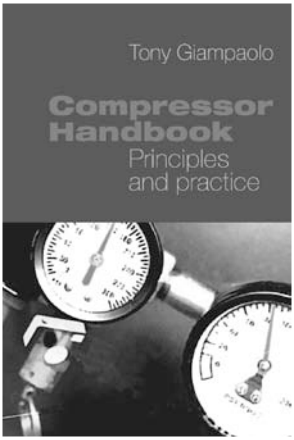

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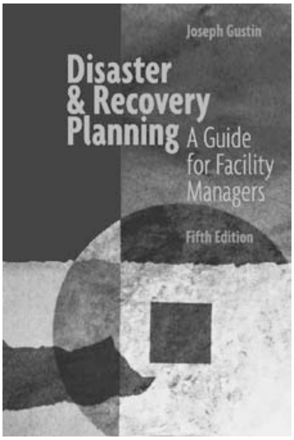

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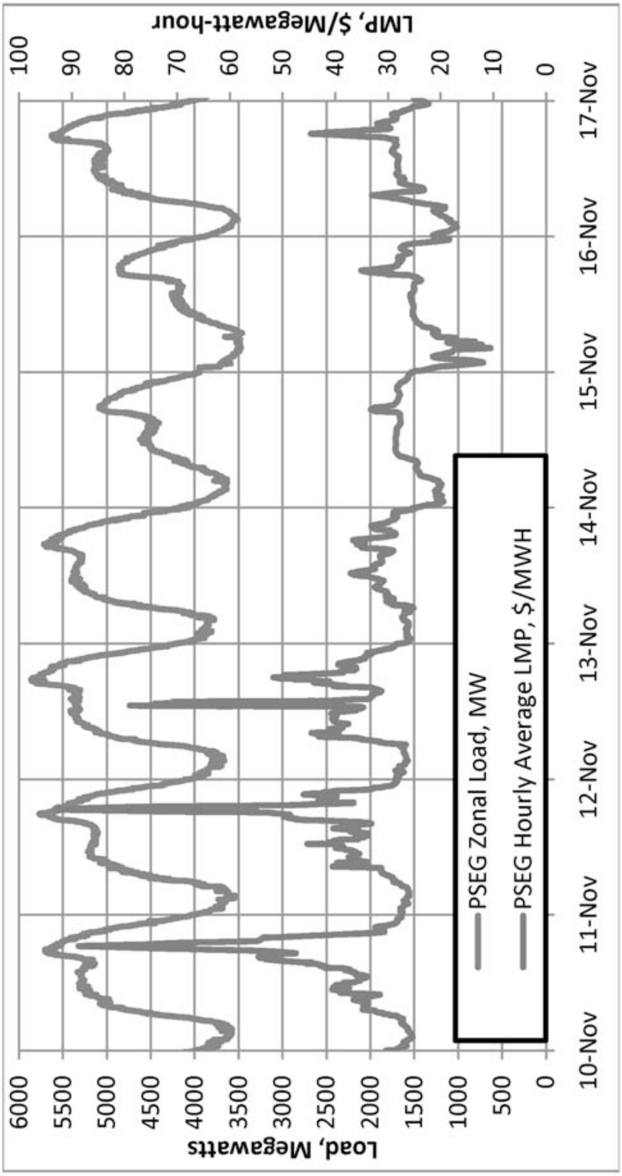

Figure 1. Grid Load and Price Variation

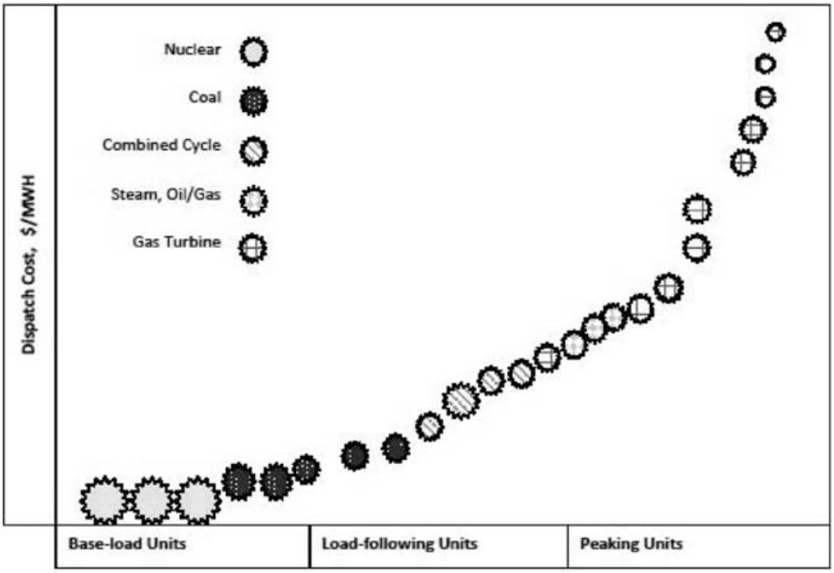

Figure 2. Generation Type and Grid Dispatch Stack

Typically these "baseload" plants would be hydro, wind, and nuclear. These plants all have high capital costs per kilowatt of capacity, but they have very low marginal operating costs. Note also that none of these is combustion-based. Thus, none generates CO_2. A few other "load following" generators may be running at their lowest output—in anticipation of higher energy demands and prices later in the day. When the sun rises, photovoltaic systems will contribute to the mix.

The load dispatcher watches voltage throughout the grid. As people wake up and go to work, power demand rises. The voltage begins to drop very slightly. The load dispatcher will raise the LMP. At $.05 to $0.10 per kilowatt-hour, more generators will be motivated to run. Coal and then gas-fired plants will come on line as the LMP exceeds each of their marginal costs to generate.

Say it's a very hot afternoon. The first people leave work and go home to make dinner. They turn on the air conditioner, turn on lights, and begin cooking, but most of the lights and cooling systems are still on at the office. So power demand rises even higher. The load dispatcher offers an LMP of $0.25 per kilowatt hour. Now even the "peaking" plants, diesel generators, and simple-cycle gas turbines can make money by operating. So they come on line. Note that these plants are the most expensive per kilowatt-hour and last to be called on since they have the highest heat rates; i.e., they are the least efficient users of fuel energy. They tend to be smaller, lighter, and more responsive, and they have lower capital costs per kilowatt of capacity. So even though they may only operate a thousand or so hours each year, they can still be quite profitable. Also note that due to their inefficiency, they tend to be the most polluting plants per kilowatt hour. Generators that are only used in emergency situations may have no emissions controls at all.

What if even more demand occurs and the load dispatcher doesn't have any more generators to call on? First, the voltage is allowed to drop. At a wall outlet one could measure the voltage as it drops from 125 Volts AC to 110 or less. What then? The load dispatcher will contact "interruptible" electric customers such as large electric furnace operators and ask them to shut down. Finally, if there are no other ways to curtail demand and no more generators, the utility will force local "brownouts" to avoid a complete system shutdown. But that is avoided long in advance by the utility's careful capacity planning.

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 best efficiency point under steady load, heat is being rejected at lower night time 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.

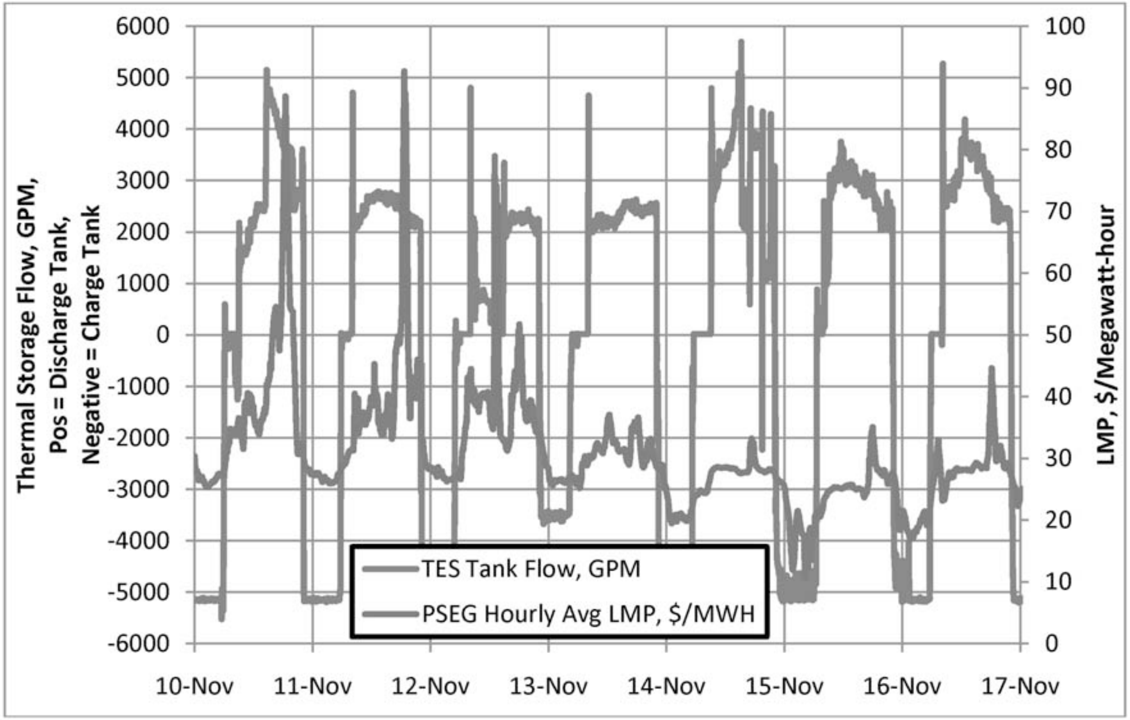

Figure 3. Thermal Storage Charge/Discharge Cycles and LMP

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, avoiding 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 (turn-down), since a pump and variable frequency drive can be controlled to a much lower level than an equivalent capacity chiller.

A BICYCLE GENERATOR HEADLAMP

A simple bicycle generator headlamp lights when the rider pedals and shuts off when the cyclist stops at a traffic light. Adding system capacitance is critical here to maintain steady lighting. So, while pedaling, the cyclist must deliver enough energy to power the lamp as well as to add some charge to a battery or capacitor. It is necessary to take advantage of the time of energy production (while pedaling) so there is energy in reserve when none is being produced (when stopped). Of course this concept is familiar in a car. The engine powers an alternator which delivers energy to the headlights as well as charges the battery. With the engine switched off, the lights and radio can operate for a while from the battery alone.

A SOLAR HOT WATER SYSTEM

A family of six might consume 50,000-100,000 Btu in a one-hour period early in the morning by 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 heat would have to be rejected back to 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 $10k.

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 for 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 rate less than we want to use it. 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 de-couple the time of production from the time of need.

A HOUSE OF WORSHIP

From the examples above, it should be obvious how the heating or cooling system for a house of worship could benefit from thermal storage. The main community gathering space tends to have a very low capacity factor with a fairly brief but high demand; i.e., it's fully occupied and needs to be heated or cooled only a few hours per day or per week. These needs are well known in advance. A heating or cooling system sized to meet the demand peak would have to be quite large and would be used relatively briefly. Instead, a smaller production system (heater, air conditioner, furnace, etc.,) could be employed along with thermal storage to increase efficiency and reliability, and to reduce life-cycle cost and possibly environmental impact.

For example, the sanctuary might have a peak cooling load of 300 tons for 90 minutes. We could meet this with two 150-ton units and run them both for less than two hours each week, or include 450 ton-hours of thermal storage and run a single 50-ton unit for nine hours the night before cooling was needed. It would have a smoother load profile, be smaller, lighter, and quieter; have 83% lower peak demand, and require a much smaller power service. Using smaller production equipment makes it more cost effective to take advantage of such things as geothermal heat pumps and solar energy. Even if we include 100% redundancy in the thermal storage system, two 50 ton units will cost less than half the price of two 150 ton units.

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 rocks 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!

TONS OF COOLING

Even the units we use to measure cooling imply thermal storage. A hundred years ago people understood that a “ton” of cooling described the amount of ice one would need to harvest, store, and then melt in the period of one day to deliver a certain rate of heat removal. So in the time before mechanical refrigeration, if a single family home used only 10 ton-hours of cooling in a season, the owner would have needed to gather 20,000 pounds of ice (nearly 100 cubic yards) during the winter and save it for use several months later! Wonder why fresh food was more common, and air conditioning was only a privilege enjoyed by monarchs?

KEY 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 de-couple 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. It can be used to operate at best efficiency, smooth out a demand profile, and use smaller equipment to meet peak demands. Adding energy storage can reduce first costs and often results in lower life-cycle 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 non-peak 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 base-loaded 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 CO_2 reduction commitments to fully optimize energy use and minimize net emissions.

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

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ABOUT THE AUTHOR

Edward T. Borer is the energy plant manager for Princeton University and is actively involved in the campus energy and carbon emissions reduction efforts. He has over 25 years of experience in the power industry, is a registered professional engineer, and holds both undergraduate and graduate degrees in mechanical engineering, as well as the CEM, CEP, and LEED^{AP} Certifications. He can be contacted in Princeton, NJ at: (609) 258-3966 or etborer@princeton.edu.