Thermal Energy Storage— Btus in the Land of kWhs

Discover how thermal energy storage works and the variations of this energy-efficient model that are becoming increasingly popular as electrical demand and cost continue to rise.

BY BRIAN SILVETTI, P.E.

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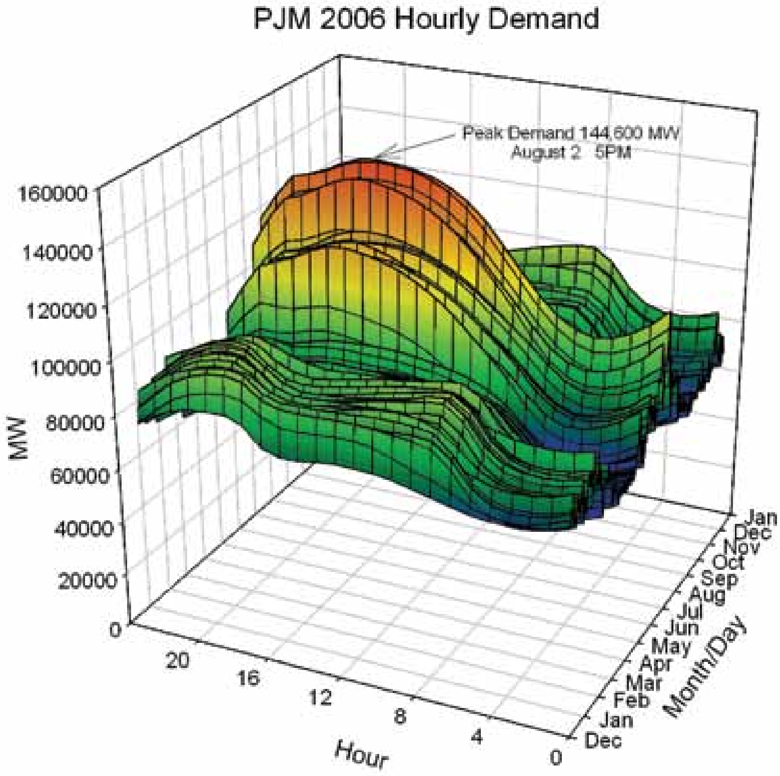
PJM 2006 Hourly Demand

Figure 1 This image illustrates the PJM utility grid generation for 2006. Record demand was met on Aug. 2, coincident with record-setting temperatures for that date. In 2011, peak generation also coincided with record-setting temperatures.

Thermal storage is one of the most successful forms of energy storage, with many thousands of installations throughout the world. It is economically justifiable on its own merits, depending primarily on demand and time-of-day utility-rate mechanisms. Thermal storage for cooling applications has received the greatest commercial interest with a broad base of manufacturing, utility and industry support.

After a brief but intense interest in energy storage during the '70s and '80s, the return of inexpensive fossil fuel dampened the sense of urgency created by insecurity about our energy future. Nonetheless, there have been some developments and successes; notably thermal energy storage for air-conditioning applications has matured into a robust commercial product, with broad manufacturing and marketing support. However, thermal storage remains a technology implemented largely within the HVAC engineering community and attracts less attention when the focus turns to energy storage in general.

Recent interest on energy storage is founded on more compelling and comprehensive motivations. Climate change, national security, energy independence, jobs and energy cost are some of the factors that are merging to reinvigorate efforts in energy-storage development. And predictably, much of the effort is related to the ability of storage to support re-

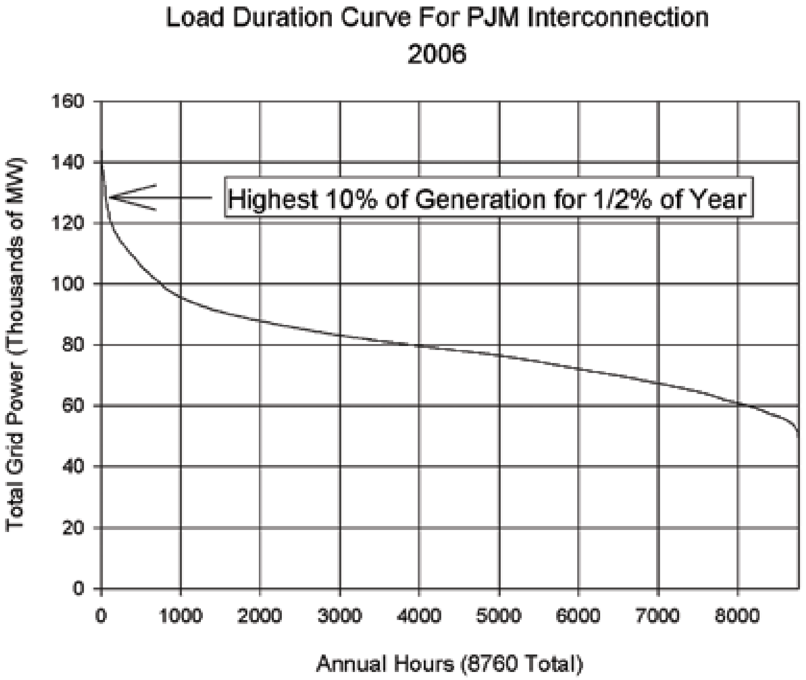

Figure 2 **This image shows the load duration curve for the same Aug. 2, 2006 record-setting day of demand seen in Figure 1.**

newable energy sources (such as wind and solar) that possess some level of uncertainty or variability, or where the availability may be temporally out of phase with demand.

Motivation for storage

The relationship between air-conditioning loads and demand on electric-utility generation is generally recognized, but the influence can be quite dramatic. Figures 1 and 2 illustrate the PJM utility grid generation for 2006. Record demand, not surpassed until the summer of 2011, was met on Aug. 2, coincident with record-setting temperatures for that date. In 2011, peak generation also coincided with record-setting temperatures.

As reinforced throughout a recent report supported by Sandia National Laboratories on behalf of the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability and the Office of Energy Efficiency and Renewable Energy Solar Technologies Program: "One of the most promising approaches to addressing the growing limitations of the electric grid and the increasing demand for renewable energy is to incorporate stationary energy-storage technologies into the U.S. electric grid."

Although record temperatures are relatively rare, temperatures approaching daily record levels occur often throughout the year. The benefit of thermal storage is magnified by the influence of temperature since it addresses the specific equipment that must respond to elevated temperatures. Furthermore, the relative benefit of thermal storage increases due to the inflated loads and the negative impact of high temperatures on efficiency and equipment capacity. As the temperature in Newark, NJ, soared to 108°F in July 2011 and air-conditioning loads skyrocketed, the energy needed to provide that cooling from modern air-cooled chiller equipment rose by about 40% compared to cooling efficiency at 85°F. Other types of storage would need to provide that higher energy demand while thermal storage can simply avoid it (see Figure 3).

Many studies evaluating the impact of energy storage on grid operations base their conclusions on the characteristics, including costs, associated with advanced batteries, pumped hydro plants or compressed air storage. However, as noted in a National Renewable Energy Laboratory report: "Thermal energy storage is sometimes ignored as an electricity storage technology because it typically is not used to store and then discharge electricity directly. However, in some applications, thermal storage can be functionally equivalent to electricity storage. One example is storing thermal energy from the sun that is later converted into electricity in a conventional thermal generator. Another example is converting electricity into a form of thermal energy that later substitutes for electricity use such as electric cooling or heating. Demand for electric-power cooling can be shifted by storing cold energy in the form of chilled water or ice during off-peak times and releasing that cold energy during times of peak demand. This effectively stores electricity with high round-trip efficiency."

The National Renewable Energy Laboratory reported in January 2009 that only sodium-sulfur batteries, pumped hydro storage, compressed-air energy storage and thermal energy storage had total installed capacities that exceeded 100 MW.

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Operational characteristics

There are several fundamental characteristics of energy-storage technologies that define their suitability for addressing electric-grid problems. Following is a very generalized description of typical thermal storage characteristics in relation to the broad spectrum of storage options—from lead-acid batteries to more than 100 MW CAES and pumped hydro.

Thermal storage exhibits relatively poor volume and mass energy density, due primarily to the fact that chilled water or ice is the most common medium for cooling storage. Water is essentially zero cost and is also the primary reason that thermal storage exhibits very low installed cost—perhaps the lowest cost of all the storage technologies. Large thermal-storage cooling systems can be installed for approximately $100/kWh.

Most thermal storage systems operate on a diurnal cycle with charge and discharge periods measured in hours, although some emergency cooling systems will discharge in 20-30 minutes. Thermal storage for cooling serves a wide range of peak cooling capacities, from small unitary systems of 5–10 kW power consumption to large district or campus systems in the range of tens of MWs.

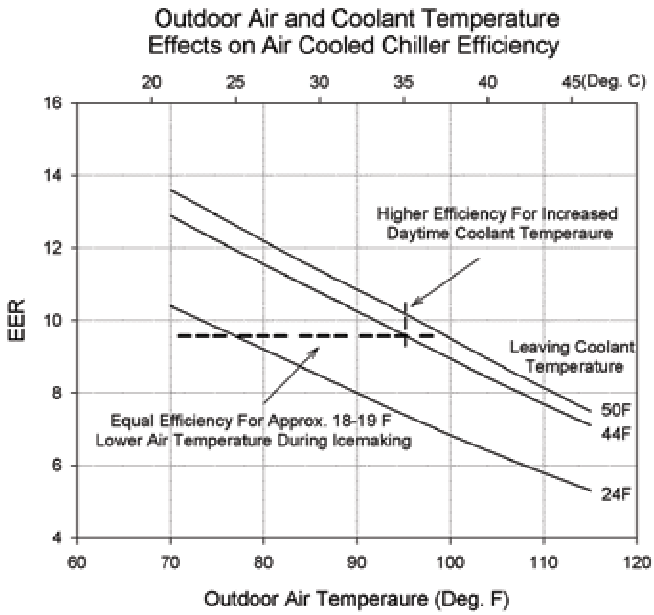

Figure 3 This chart depicts the effects the outdoor air and coolant temperatures have on air-cooled chiller efficiency.

Thermal energy storage for cooling

Thermal energy storage for cooling is currently being applied on a broad scale with commercial success based solely on its own economic benefits. Some utilities offer rebates, but generally the time-of-day dependent charges (demand/energy) incorporated into virtually all commercial electrical-rate structures provide the cost savings that justify thermal storage for cooling applications. Many installations also provide fast response to real-time pricing notification, while other recently introduced systems, with capacities designed for the unitary market, incorporate direct utility control.

There are many types of thermal-energy-storage systems. A common design employs a conventional chiller to circulate a cold glycol solution through a heat exchanger submerged within a tank of water. The heat-exchanger tubing is distributed throughout the volume of water, which gradually freezes on the exterior surface of the heat-exchanger tubing. During the day, the same glycol solution now circulates through the heat exchanger where it is cooled by the melting ice before flowing through the building coils—in turn cooling the air delivered to the occupied space. The glycol, now warmed by the air, returns to the tank heat exchanger to be cooled again. Figure 4 illustrates a commercially available storage tank, typically capable of avoiding 20–30 kW of daytime electrical power consumption. These tanks are modular. Installations may include a few or hundreds of tanks. The system in Figure 5 will shift more than 2 MW to nighttime.

“Storage for CSP plants is often achieved by accumulating thermal energy at a high temperature.”

Figure 4 **A commercially available storage tank like this one is typically capable of avoiding 20-30 kW of daytime electrical power consumption. These tanks are modular and installations may include a few or hundreds of tanks.**

Solar-heat storage

Wind energy is predicted to be the major contributor to the growth in renewable and variable electric power generation, but solar energy will also play a significant role. While solar power will typically be more coincident with peak utility-load profiles, it is often out of phase with many utilities that exhibit late afternoon peaks. This limits the value of the renewable generating asset since conventional capacity must be available to meet the peak demand. Also, individual solar-power plants are subject to rapid fluctuations in power production, a condition not well-tolerated by Rankine cycle-steam turbines commonly employed in concentrated solar-power installations.

Storage for CSP plants is often achieved by accumulating thermal energy at a high temperature. Liquids such as oil or molten salts are the most common storage mediums, but porous solids like sand or rocks have also been used.

Other storage systems

There is no energy more fundamentally renewable than the thermal energy associated with the natural climate cycles of the earth. Another family of storage technologies, underground thermal energy storage—more common in Europe than North America—takes advantage of this virtually free energy source.

There are four basic types of underground systems, including a simple tank, pit, borehole and aquifer storage, each with a wide variety of possible site-specific design features. While occasionally applied to individual residences, these systems are more often devoted to multi-dwelling or district-size ranges. The storage temperatures cover a broad span and are often in the range of 80°C–95°C for heating applications, but cooling and combined heating/cooling systems are also currently operating. Pit storage is similar conceptually, with the earth forming the sides and base of the storage volume. The pit, fitted with an impermeable liner, can be filled entirely with water or high-void porous solid-like gravel or sand.

Figure 5 **A system like this, consisting of several storage tanks, can shift more than 2 MW of electrical power consumption to nighttime.**

Aquifer storage is accomplished by injecting and extracting water directly into subterranean formations of saturated and permeable earth. The injection and extraction wells are drilled to a depth of 1,250 m and are separated by 1,300 m or more than 3/4 of a mile. While relatively rare domestically, the first commercial-scale aquifer-storage system in the U.S., designed for more than 2,000 MWh of annual cooling storage, has been operating at the Richard Stockton College in Pomona, NJ, for several years.

Tank-and-pit storage systems may be insulated, but it is obviously impossible to insulate borehole and aquifer types. Annual losses can be substantial and large installations enjoy a significant economy of scale. Of course, all of these systems, particularly borehole and aquifer designs, require an extensive evaluation of the site geology.

Although relatively uncommon, there are also systems that accumulate snow and/or ice produced in the winter, for air-conditioning the following summer.

Summary

The growth of variable or intermittent renewable-energy power production will require the deployment of other storage methods. A wide selection of storage technologies are under development for the generation side of the utility grid. On the customer end of the power-transmission network, thermal storage for cooling applications has already built a proven track record of cost-effectively resolving the demand for electricity with its availability, directly addressing air-conditioning, the primary cause of high utility demand. In addition, end-use storage technologies, like thermal storage, provide the additional benefit of reducing congestion on the transmission and distribution network, delaying the need for additional T&D construction.

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Cooling-load Considerations

In conventional A/C system design, cooling loads are measured in terms of tons of refrigeration (or kW) required, or more simply tons. Thermal energy-storage systems, however, are measured by the term "ton-hours" (or kWh), and they must be able to provide the cooling load for each individual hour as well as the totalized load over the entire day.

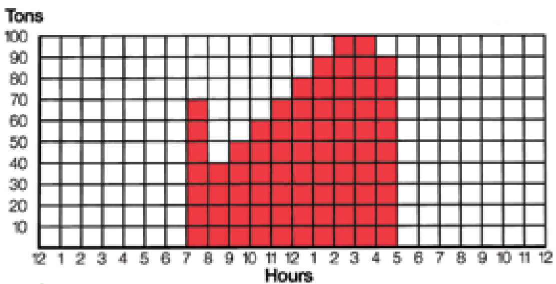

Figure 6

Realistically, no building A/C system operates at 100% capacity for the entire daily cooling cycle. A/C loads peak in the afternoon—generally 2-4 p.m.—when ambient temperatures are highest. Figure 6 represents a typical building A/C load profile during a design day.

As the image illustrates, the full 100-ton chiller capacity is needed for only two hours in the cooling cycle. For the other eight hours, less than the total chiller capacity is required. A total of 75 tinted squares each represent 10 ton-hours. A 100-ton chiller must be specified, however, to handle the peak 100-ton cooling load.

Storage systems may be designed to serve the entire cooling load during the day, but more often they serve only part of the load, with the remainder provided by a smaller chiller. In this example, a storage system only has to provide a total of 750 ton¬-hours and a peak of 100 tons for only the two high-load hours, rather than the entire day. One of the more common service procedures is reviewing the control implementation to ensure that the smaller chiller contributes its design capacity to the cooling load rather than transfer excess load onto storage.