Cool Thermal Energy Storage

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This is the thirty-fifth article inspired by a recent DOE report covering energy-saving HVAC technologies.

Thermal energy storage (TES) systems store a sizeable quantity of "cool" thermal energy that helps meet the cooling load of a building.

A typical system consists of a large vessel filled with water or brine that may contain multiple small containers (e.g., encapsulated bricks or balls) filled with a material (such as water) whose liquid/solid phase-change temperature is lower than the building's chilled-water temperature. In anticipation of periods requiring large cooling loads, typically at night, a chiller produces chilled water or brine that flows to the vessel, causing the encapsulated material to solidify (change phase) and creating a low-temperature reservoir. In other systems, an ice harvester may produce ice.

When the building requires cooling during the day, the chilled water line passes through the TES tank to chill the water and provide cooling, decreasing the chiller's load during the day. TES storage capacities of installed systems have ranged from 100 ton-hours (350 kWh) to 29,000 ton-hours (102 000 kWh).[1]

Most TES systems are ice- or water-based, with only a small fraction using a phase-change material (PCM) other than water.[1] Typically, nonaqueous PCMs are hydrated salts with a phase change temperature of 47°F (8.3°C), according to Chapter 34 of the *2003 ASHRAE Handbook—HVAC Applications*. Dorgan and Elleson[2] and the *2003 ASHRAE Handbook* describe different types of TES in greater detail.

Energy Savings Potential

TES systems can save energy in several ways, compared to conventional chillers.

Nighttime chiller operation takes advantage of lower dry-bulb temperatures (for air-cooled condensers) or moderately lower wet-bulb (for water-cooled condensers) temperatures relative to daytime values, which also reduce chiller lift. For an Atlanta climate, lower nighttime temperatures reduce air-cooled and water-cooled chiller energy consumption by an average of approximately 21% and 9%, respectively.[3] These values vary significantly depending on climate and weather.

The baseload power plants that operate at night typically have higher electricity generation efficiencies (on a primary energy basis) than the plants brought on-line to meet peak electricity demand. Consequently, displacing daytime chiller operation with nighttime operation can reduce primary energy consumption.

Electricity transmission and distribution (T&D) losses typically are higher during peak demand periods than during the night. As the power flow through transmission lines increases, the power dissipated by the lines increases by the square of the power flow. This, in turn, causes the lines to heat up, which further increases line resistance and losses. For example, data for the baseload versus peaker plant efficiency and T&D effects for two major California utilities suggest that substituting off-peak electricity consumption for on-peak consumption reduces primary energy consumption by more than 20%.[4] In practice, values can vary substantially based on the on- and off-peak generation mix of each utility.

TES can be used to increase the number of hours that chillers operate at high efficiency by actively controlling the TES discharge rate so that the required chiller output coincides with the chiller's most efficient operational regime (loading). This energy impact varies significantly with the part-load characteristics of the chiller(s) used at a given site.

On the other hand, all TES approaches experience tank thermal losses that typically range between 1% and 5% per day.[2] Furthermore, in contrast to water- or PCM-based systems that store water at temperatures similar to chilled water temperatures (e.g., around 47°F [8°C]), ice-based systems operate below the freezing point of water (32°F [0°C]). This increases the chiller's temperature lift, decreasing the chiller's coefficient of performance and increasing the energy needed to produce a unit of cooling. As a result, ice-based TES consumes approximately 50% more energy than water- or PCM-based TES (*Table 1*). If a water-based system stores water at lower temperatures than

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PCM-based systems, they will also consume moderately more energy than PCM-based TES.

Overall, the net energy impact of TES depends upon the amount of energy storage shifted to off-peak periods. A simplified study suggests that nighttime operation of a TES-chiller system sized such that the chiller could meet the integrated cooling load of an office building in Atlanta via 24-hour operation at or near full capacity could meet at least 40% of the peak period cooling demand. Using this value, PCM- or water-based TES reduces annual cooling energy consumption by approximately 10% for water-cooled systems[3,4] and 20% for air-cooled chillers relative to chillers without TES. Applied to the 0.3 and 0.1 quads of energy consumed by water- and air-cooled chillers[5], respectively, TES could reduce cooling energy consumption by about 0.05 quads. In all cases, the ice-based cooling appears to increase energy consumption because the decreased chiller efficiency outweighs other savings.

Market Factors

Analyses indicate that the economics of TES systems are sensitive to several factors, including utility rate structures, a building's daily electricity demand profile, and the cost of the space required for the system. In general, TES becomes more attractive for buildings with high load factors, high ratios of peak to average electric demand, very high peak demand charges that ratchet for several months, and ample space to accommodate a storage tank.

Table 1 summarizes approximate cost estimates for different TES approaches and similar costs for PCM-based storage systems.[2,6] Applying these values to the Atlanta office considered earlier, building load estimates indicate that a 400 ton (1400 kW) chiller could be down-sized to a 250 ton (880 kW) or 300 ton (1100 kW) chiller using 900 ton-hours (3200 kWh) or 500 ton-hours (1800 kWh) of TES, respectively. Relative to a conventional chiller system, the two PCM-based TES systems have approximately 40% and 80% price premiums. The aforementioned study of an office in Atlanta found that for electric rates of $0.055/kWh and $10/kW demand charges,

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Storage Medium	Chiller* $/ton	Installed Tank Cost $/ton-hour	Chiller Charging kW/ton	Material Cost $/ton-hour
H_2O	$200 – $300	$30 – $100	0.6 – 0.7	Negligible
Melt Ice	$200 – $500	$50 – $70	0.85 – 1.4	Low
Ice Harvester	$1,100 – $1,500	$20 – $30	0.95 – 1.3	Negligible
Encapsulated Ice	$200 – $500	$50 – $70	0.85 – 1.2	$30
PCM	$200 – $300	$100 – $150	0.6 – 0.7	$95

Note: The above prices do not include inflation. According to the U.S. Census Bureau, producer prices for capital equipment increased by about 10%.
* Does not include installation.

Table 1: Thermal energy storage cost estimates.[2,6]

PCM-based TES can reduce cooling costs by approximately 25%. If the utility rate structure is $10/kW or higher and has a 12-month ratchet, the system can pay back its cost within a few years or less.[3] On the other hand, a water-based TES system costs about 15% less, i.e., it pays back instantly. None of these calculations take into account the cost of the space for the TES system, an important consideration in many applications.

Ice-based system economics are even more sensitive to rate structures due to the system's higher operating costs. One study simulated the summertime performance of an ice-based TES system in a 55, 800f² (5184 m²) office building in Phoenix. For a rate structure with on-peak rates of $10/kW and $0.20/kWh and off-peak rates of $5/kW and $0.10/kWh, optimal operation of the TES system yielded cooling cost savings of between 15% and 19% relative to a system without TES (depending on building thermal mass assumptions).[7] Significantly greater savings accrued for a rate structure with stronger incentives to reduce peak demand.

Several issues have limited market penetration of TES systems. Ice- and PCM-based TES systems usually cost more than adding chiller capacity. This first-cost premium dissuades many owners from investing in TES. The size of TES tanks has also posed problems in many space-constrained applications (e.g., downtown office buildings), particularly for systems with lower energy density, most notably water-based systems. This would appear to be the primary driver for the installation of ice-based storage.

In addition, a lack of experience with TES may cause many facility personnel to overlook TES when considering design options. In other cases, their lack of experience operating a system with TES may make them wary of investing in TES.[8] Effective system control, including reasonably accurate load forecasting at least half a day ahead of time, is a key to reaping the operating cost savings of TES.[6,9,10]

PCM-based systems also have raised potential health/safety issues due to handling concerns and the possibility of leaks of the material out of their encapsulation and/or tank. Finally, encapsulated PCMs can gradually breakdown and stratify within the encapsulation, which reduces their thermal capacity and performance.[3]

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