Thermal Energy Storage MYTHS

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Using thermal energy storage has shifted gigawatts of power off of daytime peaks in a cost-effective manner. However, thermal energy storage (TES) market penetration is small in comparison to its potential. Why? In TES' infancy (early 1980s), a small number of manufacturers carefully researched the technology and installed equipment. In the technology's adolescent years (late 1980s and early 1990s), dozens of manufacturers, chasing the new demand-side management rebate incentives, jumped into the marketplace. These difficult adolescent years resulted in tarnished reputations and the spread of misinformation about the technology.

This article attempts to set the record straight on the myths and reality of this technology by demonstrating how TES is well-positioned to help the move towards more energy-efficient and environment-friendly air-conditioning systems.

The obvious reason for installing TES is to reduce energy costs. Although deregulation of the electric industry has created localized anomalies in energy costs, the basic reality of supply and demand is that on-peak power is more expensive than off-peak power.[1] One consistently proven aspect of TES is that it saves energy costs, which has more significance now that ANSI/ASHRAE/IESNA Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings,* and the LEED rating system are based on energy *cost* savings. Several TES projects that have won ASHRAE's Technology Award[2,3,4] detail the cost-saving aspect. However, less emphasis has been given to the reductions of equipment size and infrastructure that normally occurs.

The basic TES cooling systems that I base most of my analysis on are:

Chiller-based systems. Throughout the adolescent years of TES, a variety of systems including site-built liquid overfeed refrigeration systems, ice-harvesting equipment and others, were used successfully in other applications. However, 99% of commercial air-conditioning TES systems installed use a standard chiller to produce the cooling. Chillers are familiar, reliable, capacity rated, and competitively priced. They cool water or a glycol water solution.

Ice-based storage. For projects where space is not as much of a consideration, chilled water storage is becoming widely used.[5] However, since so much HVAC work involves retrofits where space is a concern, ice is the likely choice.

Closed system. Large district cooling systems use either water and/or ice as the storage media *and* the heat transfer fluid. These "open" systems create added hydraulic complications that need to be

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carefully addressed. However, most TES systems now separate the storage media from the heat transfer fluid, so the systems are the same hydraulically as most chiller systems.

The Myths of TES

Myth 1

Uncommon and risky. If I said TES has 100% market penetration and that you use it today, you probably would say I was crazy. Well, I would be right because a domestic hot water heater is the best example for understanding the value of *cool* thermal energy storage. (When applied to commercial air-conditioning applications, TES often is referred to as the more descriptive term "off-peak cooling.") To instantaneously heat water for a low-flow showerhead, a simple calculation shows that 18 kW of power is required (*Equation 1*) or 36 kW for two simultaneous showers.

$$\frac{[2.5\text{ gpm}\times 8.33\text{ lb/g}\times(110-60)]\,60\text{ min/h}}{3414\text{ Btu/kW}}=18.3\text{ kW}\qquad(1)$$

Even a large capacity water heater (electric for simplicity) has a 4.5 kW heater, at most. So the reduction in infrastructure for wiring and electrical power associated with it is a minimum of 4 to 1.

Although no one sizes a domestic heating element to handle instantaneous load, this is done regularly in the HVAC world. Why install a chiller system that safely (with our understandable use of "safety factors") meets a load that occurs a couple of hours per year? A simple partial storage system reduces the chiller size to something safely above the average peak daily load, which normally reduces the chiller plant size by about 40% to 50%, with the proportional savings of infrastructure that are similar to the water heater.

Myth 2

Too much space. Does the water heater in your house take up too much space? In *Equation 2*^{6} a quick calculation shows the space required for a full storage system.

$$\text{Full}=\frac{70\text{ ft}^2\text{/tank}^{(\text{ref. }6)}}{500\text{ ft}^2\text{/ton}\times 20\text{ ton/tank}}=0.70\%$$

$$\text{Partial }(33\%\text{ of Peak})=0.70\times 33\%=0.23\%\qquad(2)$$

> Instead of adding a safety factor of 20% to the cooling plant on every job, and paying the price of oversizing for the life of the building, downsize the actual size by 20% and add storage.

Storage systems in retrofit applications are usually "partial storage" and normally are sized to handle about one-third of the peak load, yielding 0.23% of occupied space needed for storage. A 1,000,000 ft^2 (93 000 m^2) building needs only about 2,300 ft^2 (214 m^2). For a 2,000 ft^2 (186 m^2) home, the water heater takes up 5 ft^2 (0.5 m^2) or 0.25%. So for off-peak cooling (OPC) using 33% partial storage, the space needed is about as much proportionately as the water heater in a house.

Myth 3

Too complicated. Let's go back to the water heater. Is it complicated? No. It has a reliable, undersize heating element that creates heat whenever the inventory drops below 95%.

In a partial storage OPC system, a reliable undersized cooling element (chiller) runs whenever the inventory drops below 95%. TES tanks are simply thermal capacitors with no moving parts. With partial storage, no on-peak control malfunction can occur because there is no full-size chiller to accidentally set a massive electrical peak. What can complicate the system is mismatching the control complexity with the aptitude of the eventual operator. Installing a 50% sized chiller creates a major advantage in demand cost savings, which is a good goal for a small application (such as a school with a janitor). A large OPC system can handle a more complex control strategy, but that is where problems always occur. A design engineer spends hours figuring out the precise, logical way to save the most money while working with a complicated rate structure. Think how incomprehensible the strategy will be to a third-shift operator when some sensor fails (see sidebar "Designing for Success").

Myth 4

Lack of redundancy (risk) with partial storage. Almost any OPC system can meet the same redundancy criteria as a conventional system at a comparable cost. Obviously, in a conventional system with one chiller where the chiller is inoperable, you are out of luck. It is the same with a one chiller storage system. However, let's look at a conventional system with a calculated design day load of 1,000 tons (3500 kW). A reasonable conventional design would be three 400-ton (1400 kW) chillers and an equivalent partial storage system could be two 400-ton (1400 kW) chillers and 3,500 ton-

The 'KISS' Principle

Designing For Success

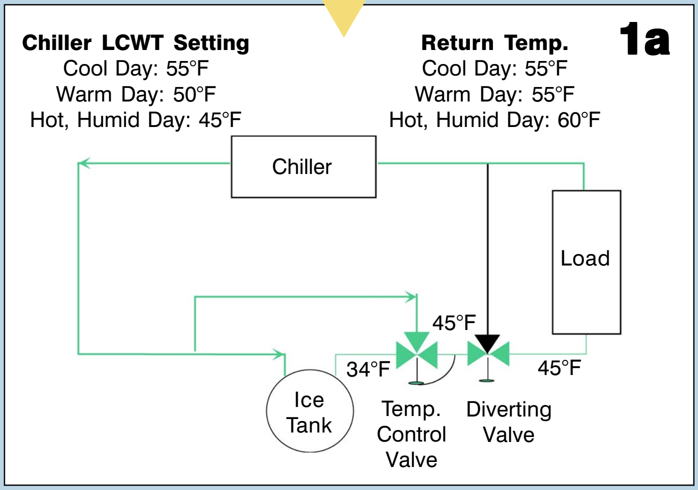
The best example of a well-designed controller for an operator (school janitor) is a three-position switch, located next to the ice inventory meter, labeled "cool day—warm day—humid hot day." The controller simply changes the leaving chilled water temperature on the upstream chiller setting from 55°F to 50°F to 45°F (13°C to 10°C to 7°C), which changes the control strategy from full storage to partial storage-ice priority to partial storage-chiller priority (*Figures 1a–d*). Because no penalty exists for starting with a full charge of storage every morning (as with other TES technologies outside of the scope stated previously), there is no fear of guessing wrong, just change the setting that morning.

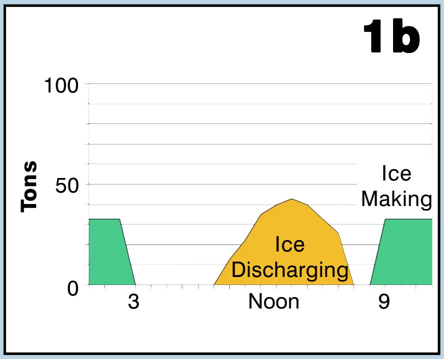
The main goal for this project was to take advantage of a large difference in energy charges ($0.12 on-peak/$0.06 off-peak). *Figures 1b, 1c* and *1d* illustrate the success of the strategy. Although the strategy wasn't "optimal," it was close. And, it worked like a charm.

I can't stress enough the "Keep It Simple Stupid" (KISS) principle. My advice is to keep the controls as simple as possible but to install simple real-time feedback on energy use information for the operators (for example, real-time total building kW). (The real-time game of "what is causing that electric peak?" is fun. Getting a call from the boss about an outrageous electric bill from two months ago is not).

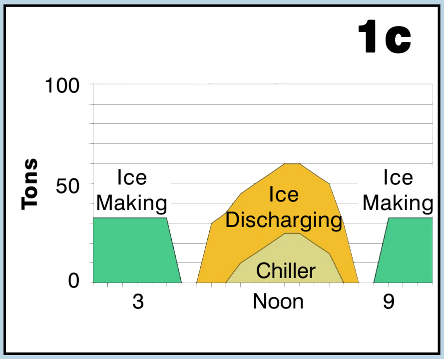
With feedback, operators stay interested and tune up a simple system. OPC systems are different, but not necessarily more complex. Owners and operators who are aware of the differences can save a lot of money.

Discharge Cycle

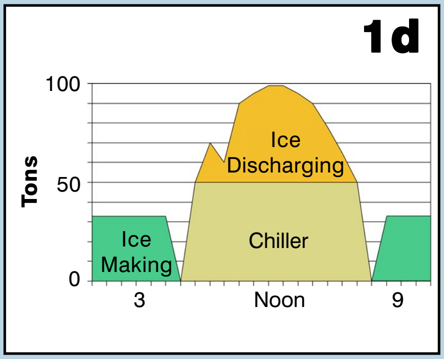




Full storage, cool day.



Partial storage, ice priority, warm day



Partial storage, chiller priority, hot, humid day

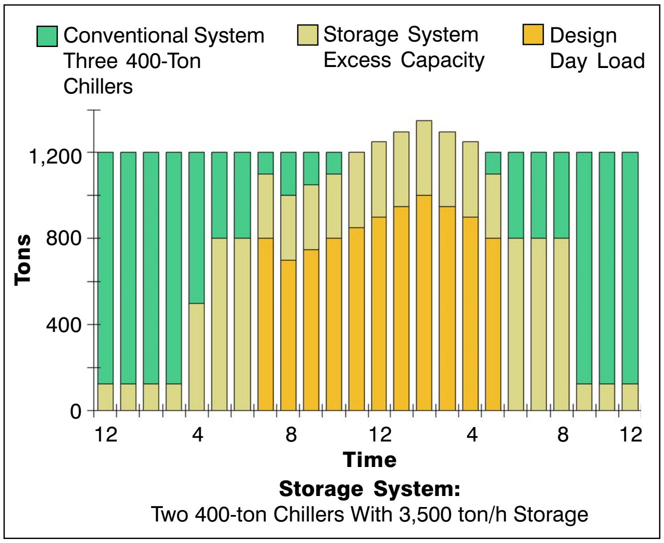


Figure 2a: Excess capacity on design day.

hrs (12 300 kWh) of ice storage. *Figure 2a* shows the maximum capacity for both systems as compared to the design day load profile. Though the 1,200-ton (4220 kW) system could create more ton-hrs in the 24-hour period, it is clear that the storage system is more than what is required even on a design day.

The next concern is equipment failure. *Figure 2b* shows if a chiller failed on the conventional system, or storage was unavailable in the storage system, both would have two 400-ton (1400 kW) chillers to handle the load, and for six of the 11 hours, the system would be short some capacity. If the component that failed on the storage system were a chiller, the remaining chiller and storage would be able to meet the full load for eight of 11 hours. Therefore, the systems are quite similar and both systems would need 500-ton (1760 kW) chillers (three or two), instead of the 400-ton (1400 kW) machines, to have "n+1" redundancy.[7]

Myth 5

Too expensive to install. It is difficult to obtain real costs for equipment because companies don't want to publicly show their "hand." Although many documented case studies demonstrate lower first cost,[3] it is easier to look at it using simple numbers. In most applications, the chiller system can be downsized by 40% to 50%. However, let's use the 33% reduction in the earlier example. In this case, we have downsized the refrigeration plant by 400 tons (1400 kW) including chiller, cooling towers, cooling tower pumps and electrical capacity to all units. Using $900/ton ($256/kW) for an installed cost for a system yields:

Non-Storage System

Three 400-ton Chillers × $900/ton = $1,080,000

Partial Storage System

Two 400-ton Chillers × $900/ton = $720,000
3,500 ton-hr of Ice Storage × $100/ton-hr = $350,000
$1,070,000

Specific applications and locations will vary the installed costs but the point is the cost can be essentially the same when experienced OPC contractors compete on new construction projects (more than 400 tons [1400 kW]). In retrofit projects, as with almost all energy efficiency upgrades (excluding lighting), there should be another reason to go forward for the paybacks to be reasonable, i.e., aging chiller plant, CFC replacement, building expansion, strained electrical supply, etc.

Myth 6 **Does not save energy.** When analyzing energy savings with OPC, you must consider both energy used at the building and energy used at the source of generation at the power plant. The reason is simple. Most energy-efficient products reduce energy use but do not change *when* energy is used. As an industry, we have done a poor job of relaying the energy saving benefits of OPC beyond the meter. *Site* energy savings may or may not occur. *Source* energy savings almost always occur.

Site Energy Savings

Is the goal to save the most *energy* or *energy costs*? Clearly the owner's answer is the latter. However, energy-efficiency funding from most states is based on kWh saved. With thermal storage, optimizing for energy savings can be done but often is not the same as maximizing energy cost reduction. So let's review a design maximizing energy savings for air-cooled and water-cooled applications.

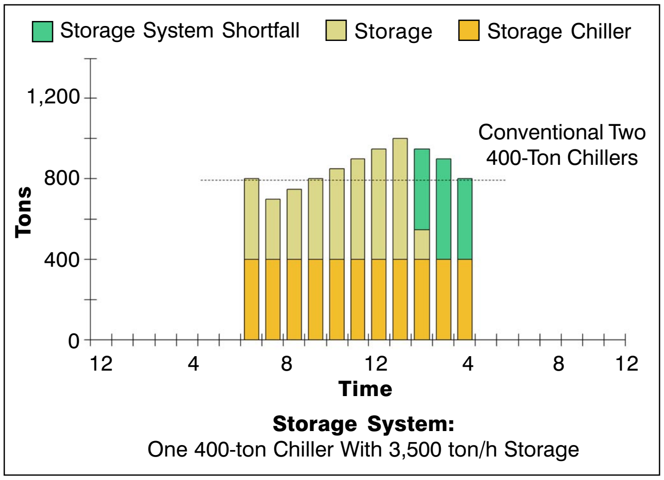


Figure 2b: Capacity on design day with one chiller failure.

First, an air-cooled chiller operating at ARI design conditions, 95°F/45°F (35°C/7°C) (Point A in *Figure 3*), uses the same kW/ton at ice-making conditions of 78°F/25°F (26°C/–4°C) (Point B) (*Figure 3*). Therefore, a 17°F (9°C) change in dry bulb gives equal efficiency for ice making. In much of the country, the ambient day to night swing is 20°F (11°C). Because the swing is sinusoidal, the average for the on-peak hours versus the ice-making hours make the average temperature swing more like 12°F to 14°F (7°C to 8°C). If you then factor in:

1. Undersized chillers are fully loaded for a majority of the hours of operation, normally their most efficient condition.

2. Chillers in a partial storage system normally operate upstream of ice storage. Therefore, the chillers cool the upper half of the delta T, and have higher on-peak efficiencies than if they were producing 45°F (7°C) liquid (Point C in *Figure 3*).

3. Extreme part-load conditions can be met fully with ice to avoid short cycling of chiller equipment (0% to 20%), which is clearly very inefficient.

For water-cooled OPC applications, the argument is less clear initially for site energy savings. Ambient wet-bulb temperature only decreases about 5°F to 7°F (3°C to 4°C) from day to night. Therefore, this decrease does not make up for the lower evaporator temperatures required for ice making, yielding about a 15% "penalty" (*Figure 4*) (Point A to B). However, the most important point is the amount of ton-hrs per year that are actually met with ice in a design focused on energy savings. In a standard chiller priority, partial storage system, where a 50% sized chiller(s) would work, but a 60% sized chiller is installed, a simple bin analysis shows that the amount of ton-hrs per year in an office building or school above 60% is only about 20%. So with the ice-making penalty for air-cooled chillers arguably at 0%, and 15% for water-cooled, the total ice-making penalty for water-cooled is 20% of 15% or about 3%. Even with the extra pumping required to put cooling into storage, when the points made earlier for air-cooled are factored in, it is arguable that the water-cooled difference drops to nil.

Routine oversizing of chillers causes related components to be oversized including condenser pumps, and cooling towers and transformers, which likely will never run at full load for the life of the system. Right-sizing chiller capacity is capable of saving lots of energy, as discussed by Tom Hicks.[8] The best way to conceptualize the energy advantages of "right-sizing" a system with storage is to compare it to the value gained by using variable frequency drives (VFD) on motors. VFDs vary the *speed* to match part-load conditions: storage allows varying the *time* at full load, of a smaller cooling plant (which is like having VFDs on the chiller, condenser pump and cooling tower fan). Major advantages can be captured here that are yet to be quantified by accurate simulations.

Source Energy Savings

The California Energy Commission released a report[9] in 1996 that clearly concluded that, for two of the major California utilities, it is 8% to 30% more efficient to create and deliver a kWh during off-peak hours than during on-peak hours. The combination of using more efficient base load generation plants, lower transmission and distribution line losses and cooler nighttime temperatures combine to create more efficient nighttime generation. Therefore, if we assume that a building uses the same amount of kWh before and after an OPC system is installed, major "source energy" savings exist for each kWh shifted to off-peak. In addition, there are environmental benefits. In regards to an OPC installation in Manhattan, Ashok Gupta of the Natural Resources Defense Council stated, "Peak shaving results in lower emissions, because some of the plants used to meet demand peaks are among the dirtiest in the city."[10] In response to these findings, California's 2005 release of the Title 24 energy code will value the relative cost of energy for every hour of the year (instead of a flat rate as allowed in 90.1), otherwise known as "time dependent valuation." With relative costs of three to four times as high on summer afternoons, the code will surely drive designers to use more efficient, off-peak power and OPC.

Myth 7

Electric rates may change and negate savings. Electric rates will change. The realities of supply and demand will not. In the past, essentially all monopolistic utilities with decades of experience had rates that were dependent on time. Demand charges make peak power more expensive, albeit only for commercial and industrial customers. On a commercial electric bill, the demand portion of the bill can often equal 50% of the total, so *when* you use power is almost as important as how much. Even monopolies realized the dramatic cost of peak power and the cost advantages of raising load factor (a measure of effective use of installed generating capacity). In the future's (more) competitive environment, the economics of unregulated generation will be driven even more by supply and demand.

Demand response programs, which call for reductions of 10% of building loads for four hours on short notice for a given financial incentive, are clear evidence of this and are tailor made for partial storage OPC systems. Until a substantial oversupply of generation exists (which is not cost effective), or the use of power becomes relatively even for day and night (not in my lifetime), a large difference in the cost of on- and off-peak power will exist. Short-term anomalies such as flat rates may occur temporarily but they will pass (even the flat rates often take into account building load factor, i.e., lower flat rate for better load factor). Also remember, in new construction, there is little or no first-cost premium, which further reduces the critical nature of exact energy costs.

Myth 8

Modeling doesn't show energy savings. Often that is true and the reason is simply because many modeling programs, including DOE-II, were never really designed to model all the advantages of storage. DOE's newest program, E-Plus will soon have the capabilities to model storage well and the true energy picture should be clearer.

Conclusion

Off-peak cooling uses low-cost electricity that is efficient to generate and cleaner to make, clearly qualifying it as a "green" technology. TES is a technology that has grown up. A lot of lessons have been learned, and it is up to manufacturers to disseminate information on best practices. Only the most advanced and committed operators require an optimal control system to

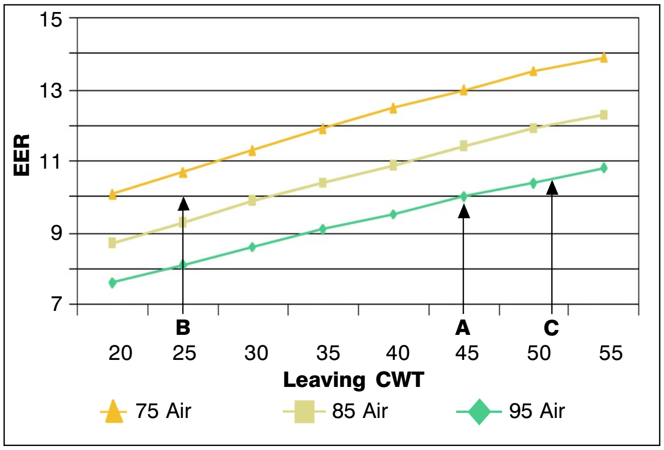


Figure 3: EER of air-cooled chillers (includes heat rejection).

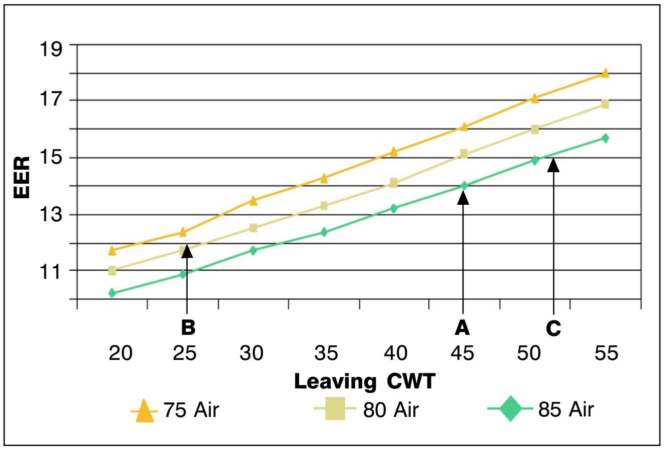


Figure 4: Water-cooled chiller (comp. only).

save every possible dollar. The remaining users require control complexity to be about that of an electric water heater.

Maybe the best way to conceptualize and justify the real-world application of this technology is this: instead of adding a safety factor of 20% to the cooling plant on every job, and paying the price of oversizing for the life of the building, downsize the actual size by 20% (instead of 40% to 50%) and add storage. With no loss of redundancy and good gains in energy cost reduction and full-load operation, the OPC system gains operational flexibility and reduces load on the electric grid. The investment is in a usable asset (storage) instead of a dormant one, namely a backup chiller. OPC accomplishes its goals at a fraction of the cost of other more "sexy" technologies (fuel cells, microturbines), which have a long way to go on the learning curve. TES used for OPC is a proven, simple and practical solution to rising energy costs.

References

1. Audin, L. 2003. "Central plant savings." *Engineered Systems* (5).

2. Evans, W. 1998. "Ice storage cooling for campus expansion." *ASHRAE Journal* 40(4).

3. Hersh, D. 1994. "DDC and ice thermal storage systems provide comfort and energy efficiency." *ASHRAE Journal* 36(3).

4. O'Neal, E. 1996. "Thermal storage system achieves operating and first-cost savings." *ASHRAE Journal* 38(4).

5. Bahnfleth, W. 2002. "Cool thermal storage: is it still cool?" *HPAC Engineering* (4).

6. CALMAC. 2003. *IceBank® Performance Manual*.

7. Silvetti, B. 2002. "Application fundamentals of ice-based thermal storage." *ASHRAE Journal* 44(2).

8. Hicks, T. 1999. "Small steps bring giant leaps." *Building Operating Management* Sept.

9. California Energy Commission. 1996. *Source Energy and Environmental Impacts of Thermal Energy Storage*, Report #500-95-005 www.energy.ca.gov/reports/reports_500.html.

10. Gupta, A. 2002. "On Avenue of the Americas, the iceman cometh." *New York Times* March 17. ⬢