Thermal Energy Storage

A new application of an old idea

As the second-most populated country on this planet, India's ever-growing demand for energy has shown no signs of dwindling. A clearly strained electricity infrastructure is supplying the sixth-largest electricity consumer in the world, and it shows. Demand for power far exceeded supply in 2010. India had a power shortage of about 10% on average and a deficit that increased during peak load to 13.3%. The air-conditioning market is evolving rapidly and utilities cannot keep up with the pace, so rolling blackouts and outages continue to put millions in the dark every day. Even with the Ministry of Power's massive investments in nuclear reactors and renewable solutions like wind, electricity losses during transmission range between 30 & 40%.

So far, commercial property owners and building managers in major cities across India have responded to blackouts by using backup generators. They have become a necessity in a country that experiences power cuts for four to six hours at a time. The cost of a backup generator hovers around $250 per kVA (Rs 12,000) and operating costs are roughly 33 cents per kWh (Rs 16), which is over six times the cost of electricity from the Grid. In lieu of large, expensive generators sized to meet peak demand for air-conditioning, perhaps the answer to India's power deficiencies and stressed-to-capacity grid lies with incorporating a technology that has already been successful for decades.

Thermal energy storage (TES) is a new application of an old idea to store energy. Storing energy is an integral part of our world from the food in our cupboard to the water in our wells. It's how supply and demand is balanced. In a building, thermal energy storage shifts cooling loads to off-peak hours, lowering not just peak demand during the air-conditioning season, but also source energy usage (energy produced at the power plant). It uses a standard chiller to produce solid ice at night during off-peak periods when the building's electrical loads are at a minimum, power plants are running more efficiently and electricity is more abundant. The ice is built and stored in modular storage tanks to provide cooling and help meet the building's air-conditioning load requirement the following day, allowing chillers and backup generators to be down sized.

Thermal energy storage is a proven method of storing energy with over 6,000 installations worldwide. By increasing a building's "Load Factor" (Average Load / Peak Demand), it improves a user's negotiating position with energy suppliers. The higher the load factor, the more attractive the customer. TES systems are electric suppliers' best option for increasing load factors on their generating equipment and avoiding the costs of new generating plants. In fact, a good load factor lowers peak demand so that the size of backup generating equipment and chillers are smaller.

These systems can not only cut cooling costs, but costs of capital outlays are less than non-storage systems when suitably designed for new commercial and industrial buildings. In fact, engineers can specify half-size chillers operating 20 to 24 hours a day versus full-size chillers operating only 10 or 12 hours per day. In retrofit applications, TES systems can often provide cooling for increased loads to a building without adding chiller capacity. Furthermore, if a building owner plans to generate his own power or have a backup generation system, storage can displace a portion of the initial cost for a system. Table 1 shows approximate installed costs of chillers, storage and backup generation on a $/unit basis for a hypothetical 1,000 tons (350 kW) building project. The most important point is that the thermal energy storage system often costs less than a conventional system. Savings from down sizing the chiller plant and backup generation makes storage a cost-effective option with far reaching benefits to the owner and society.

The Concept Behind Stored Cooling Systems

In conventional air-conditioning system design, cooling loads are measured in terms of Tons of Refrigeration (kW) required, or more simply, Tons. Thermal energy storage systems, on the other hand,

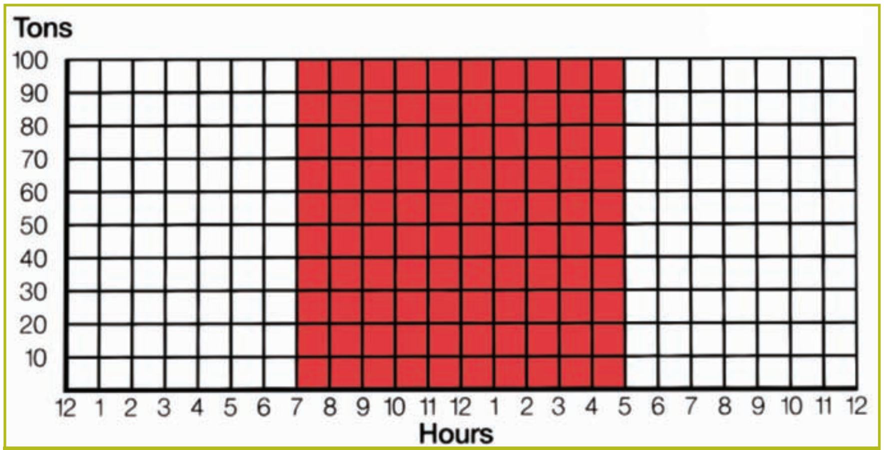


Fig. 1

Installed Cost Summary - 1000 Ton Peak with Back-Up Gen
Non-Storage System: 3-400 ton Chillers, 750 kW Peak*
Storage System: 2- 400 ton Chillers, 3500 ton-hr Ice Storage, 375 kW Peak* Reduction

	$/ton	$/tonHr	$/Peak kW	Non- Storage System Cost	Storage System Cost
Chillers	$700			$840,000+	$560,000
Storage (8.75ton-hr/ton)	$875	$100	$875		$350,000
SubTotal Chiller Plant Cost				$840,000	$910,000
Less 375 kW* Back-Up Generation			$250*	-	-$93,750*
Total Chiller Plant Cost				$840,000	$816,250

Table 1: Reference MacCracken, M. 2004 'Thermal Energy Storage in Sustainable Buildings.' ASHRAE Journal 2004. Adapted for the India market.
*Approximation includes chiller and all ancillary power. The costs of back up generation is in U.S. costs.

are measured by the term Ton-Hours (kW-h). Fig. 1 represents a theoretical cooling load of 100 tons maintained for 10 hours, or a 1,000 ton-hour cooling load. Each of the 100 squares in the diagram represents 10 ton-hours.

Realistically, no building air-conditioning system operates at 100% capacity for the entire daily cooling cycle. Air-conditioning loads peak in the afternoon generally from 2:00 to 4:00 p.m. when ambient temperatures are highest. Fig. 2 represents a typical building air-conditioning load profile during a design day.

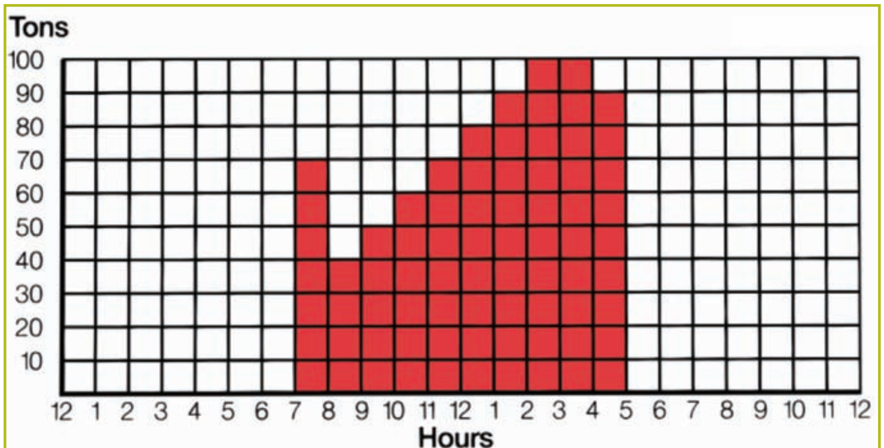


Fig. 2

As you can see, 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. If you count the tinted squares, you will total 75, each representing 10 ton-hours. A 100 ton chiller must be specified, however, to handle the peak 100 ton cooling load. "Diversity Factor" is defined as the ratio of the actual cooling load to the total potential chiller capacity, or:

Diversity Factor (%) = Actual Ton Hr. / Total Potential Ton-Hr.=750 / 1,000

This chiller, then, has a Diversity Factor of 75%. It is capable of providing 1,000 ton-hours when only 750 ton-hours are required. If the Diversity Factor is low, the system's cost efficiency is also low. The lower the Diversity Factor, the greater the potential benefit from a TES system. Dividing the total ton-hours of the building by the number of hours the chiller is in operation gives the building's average load throughout the cooling period. If the air-conditioning load could be shifted to the off-peak hours or levelled to the average load, less chiller capacity would be needed, 100% diversity would be achieved, and better cost efficiency would result.

Full Storage vs Partial Storage

There are a number of control strategies that can be utilized to leverage the benefits of thermal energy storage. However, there are two basic approaches that define the common limits of the system design. The peak demand savings (kW) will determine which control strategies are best for the project. When savings justify a complete shifting of air-conditioning loads, a conventionally sized chiller can be used with enough energy storage to shift the entire load into off-peak hours. This is called a full storage system and is used most often in retrofit applications using existing chiller capacity. Fig. 3 shows the same building air-conditioning load profile but with the cooling load completely shifted into 14 off-peak hours.

The chiller is used to store ice during the night, which then provides the required 750 ton-hours of cooling during the day. In this case, the average load has been lowered to 53.6 tons (750 ton-hours / 14 = 53.6). The chiller does not run at all during the day, which results in significantly reduced demand charges.

In new construction, a Partial Storage system is usually the most practical and cost-effective load management strategy. In this case, a much smaller chiller is allowed to run at any hour of the day. It charges the ice storage tanks at night and cools the load during the day with help from stored cooling. Extending the hours of operation from 14 to 24 results in the lowest possible average load (750 ton-hours / 24 = 31.25), as illustrated by the dotted line in Fig. 4. Demand charges are greatly reduced and chiller capacity can often be decreased by 50 to 60% or more.

Although the building's average 24 hour load is 31.25 tons, the chiller's actual capacity is slightly

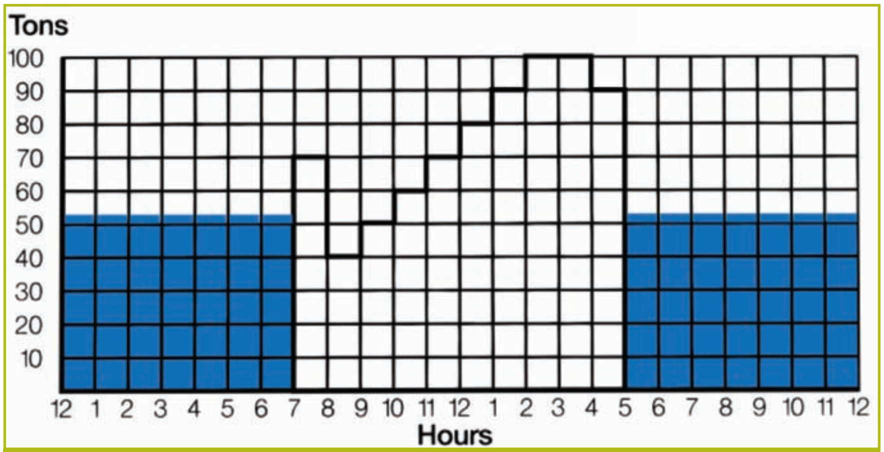


Fig. 3

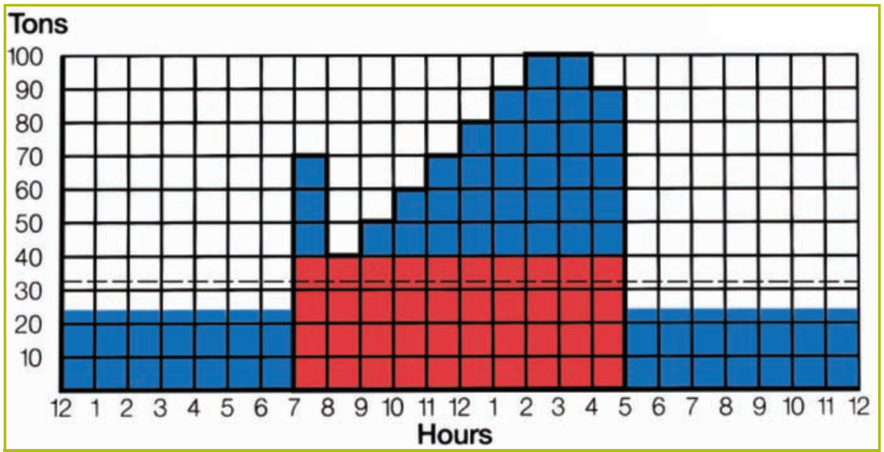


Fig. 4

higher during the day and lower at night. This is because of the chiller's 30 to 35% de-rated capacity for ice making.

How do Thermal Energy Storage Systems work!

Thermal energy storage systems come in many sizes ranging from 45 to more than 500 ton-hours. At night, water containing 25% ethylene glycol is cooled by a chiller & circulated through the heat exchanger, extracting heat until about 95% of the water in the tank is frozen solid. The ice is built uniformly throughout the tank by the temperature averaging effect of closely spaced counter-flow heat exchanger tubes, as illustrated in Fig. 5. Water does not become surrounded by ice during the freezing process & can move freely as ice forms, preventing damage to the tank.

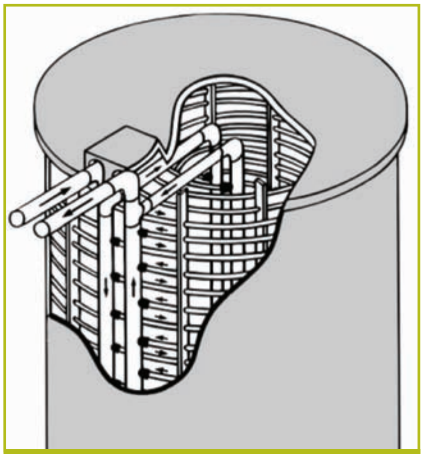


Fig. 5

Typical flow diagrams for a Partial Storage system are shown in Fig. 6 & 7. At night, the water-glycol solution circulates through the chiller and the tank's heat exchanger, bypassing the air handler coil. The fluid is 25^{0}F & freezes the water surrounding the heat exchanger.

The following day, the stored ice cools the solution from 52^{0}F to 34^{0}F. A temperature modulating valve set at 44 F in a bypass loop around the tank permits a sufficient quantity of 52 F fluid to bypass the tank, mix with 34 F fluid, and achieve the desired 44 F temperature. The 44 F fluid enters the coil, where it cools air typically from 75 F to 55 F. The fluid leaves the coil at 60 F, enters the chiller and is cooled to 52 F.

While making ice at night, the chiller must cool the water-glycol solution to 25 F, rather than produce 44 F or 45 F water

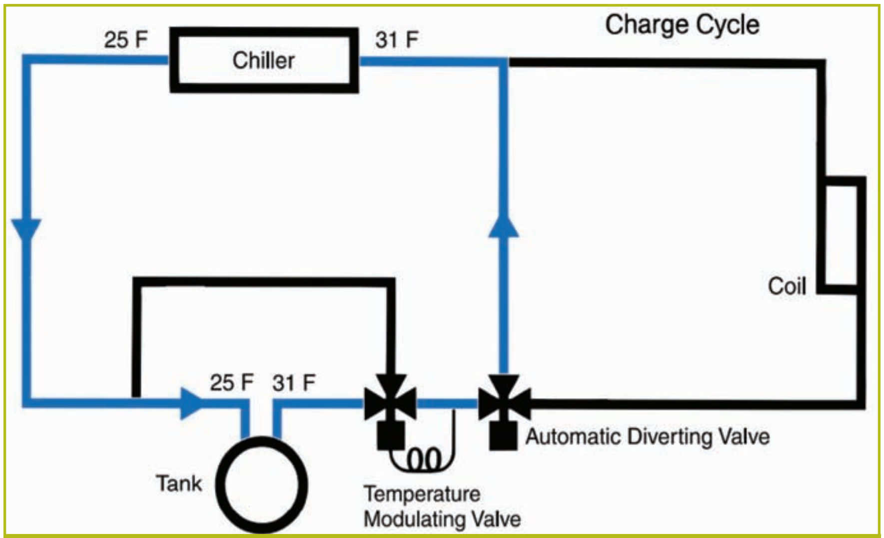


Fig. 6

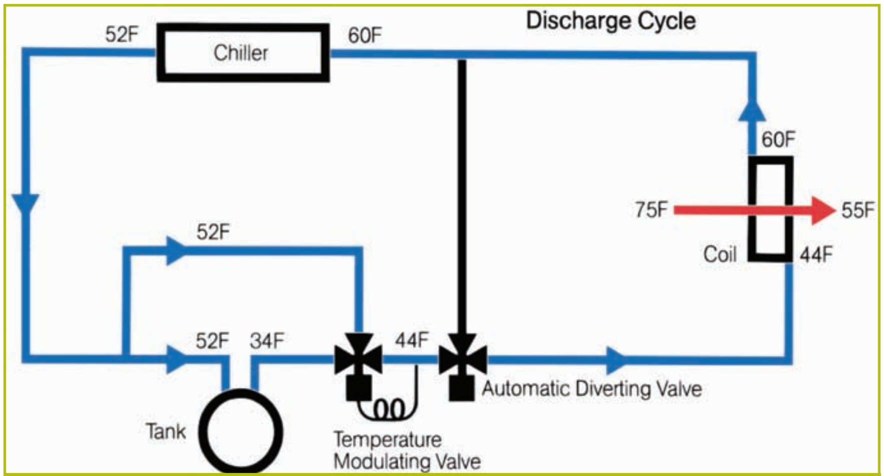


Fig. 7

temperatures required for conventional air-conditioning systems. This has the effect of "de-rating" the nominal chiller capacity by approximately 30 to 35%. Compressor efficiency, however, will vary only slightly because lower nighttime temperatures result in cooler, more condense temperatures and help keep the unit operating efficiently.

The temperature-modulating valve in the bypass loop has the added advantage of providing unlimited capacity control. During mild temperature days, the chiller is capable of providing all the necessary cooling for the building without assistance from stored cooling. When the building's actual cooling load is equal to or lower than the chiller's capacity, all of the system coolant flows through the bypass loop, as show in Fig. 8.

The glycol recommended for the solution is an ethylene glycol-based industrial coolant, which is specially formulated for low viscosity and superior heat transfer properties. These contain a multi-component corrosion inhibitor system which permits the use of standard system pumps, seals and air handler coils. Because of the slight difference in heat transfer coefficient between water-glycol and plain water, the supply liquid temperature may have to be lowered by one or two degrees. This is easily achieved by the ice.

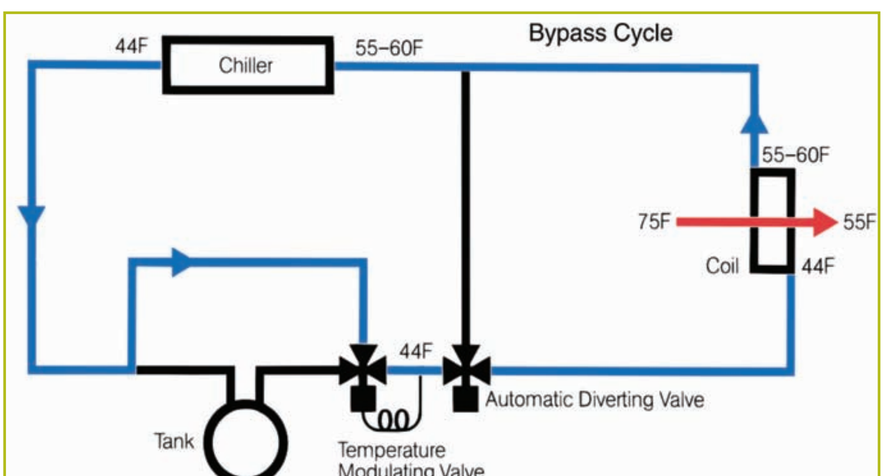
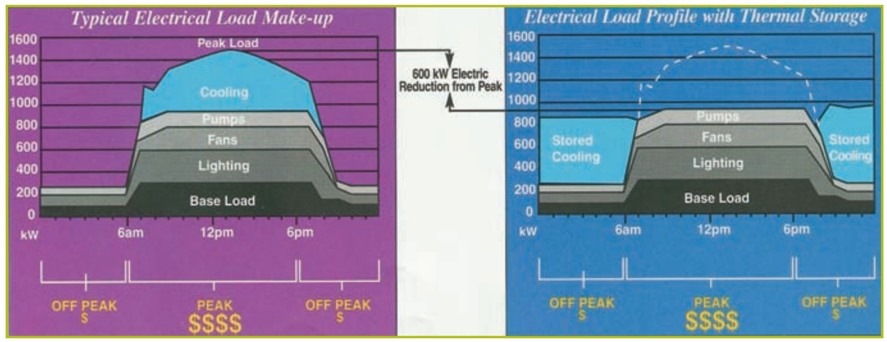


Fig. 8

Reducing Air-Conditioning Costs and Energy Use

Off-Peak Operation

Running the chiller at night substantially reduces electrical costs because energy is used off



peak when electric generating facilities are typically under-utilized by 50% or more. This results in substantial operating costs savings and a reduction in at least some of

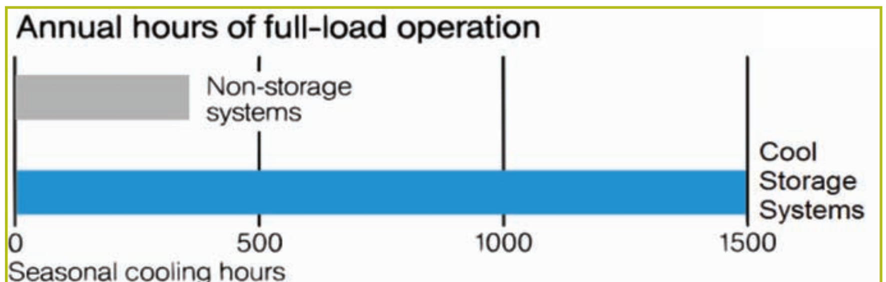


Fig. 9

the demand stress that burdens India's electrical grid during peak daylight hours. In general, TES increases a building's load factor while simultaneously decreasing its demand for peak energy. With demand charges in the range of $4 to $6 per kVA (Rs 200 to 300), the savings of storing off-peak electricity becomes a substantial return on investment to the building owner. For the similar upfront costs of backup generation, TES reduces building operation costs by lowering peak demand.

Constant Full-Load Operation

On-off cycling and capacity modulation occurs throughout the day in most air-conditioning systems in response to the cooling load of the building. Therefore, most air-conditioning systems operate within their most efficient range less than 25% of the time, as seen in Fig. 9. With TES systems, the chiller runs at or near full load (peak efficiency) continuously, eliminating the inefficient cycling that accompanies part-load operation.

Nighttime Condensing Temperatures

Air-cooled chillers perform most efficiently when the outdoor temperatures are relatively low. Operation at night with 20 degree lower condensing temperatures can improve energy efficiency typically by 2 to 8% over non-storage systems operating during the day, as illustrated in Fig. 10.

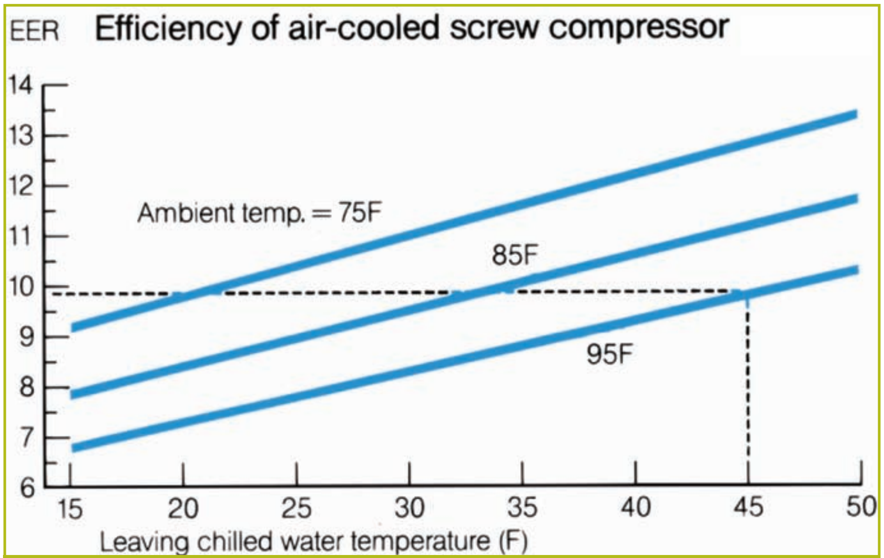


Fig. 10

Cold Air Distribution

The use of 44 F air in the duct system rather than the usual 55 F air permits further savings in initial and operating costs. This colder air is achieved by piping low temperature (36 F to 38 F) water-glycol solution to the air handler coil. The 44 F air is used as primary air and distributed to a high induction rate diffuser or a fan-powered mixing box, where it is fully mixed with room air to obtain the desired room temperature. The 44 F primary air requires much lower airflow than 55 F air. Consequently, the size and cost of the air handlers, motors, ducts and pumps may be cut by 20 to 40%. Colder air also lowers relative humidity; thus, occupants feel comfortable at higher, energy-saving thermostat settings. The Electric Power Research Institute reports that "overall HVAC operating costs can be lowered by 20 to 60% by using ice storage and cold air distribution."

Benefits Electric Suppliers and the Environment

TES systems conserve energy for the generators of electricity as well as the customer. Generation plants operating on-peak have much higher heat rates (fuel BTUs required per kWh generated) than energy generated at night. A report by the California Energy Commission (CEC) revealed that summer peak heat rate of a large west coast utility was 11,744 BTUs per kWh as opposed to its off-peak heat rate of 7,900 BTUs per kWh. This means that during the summer months, off-peak generation of electricity consumes up to 30% less fossil fuel per kWh than during peak periods. The CEC report further concluded that TES could save enough energy in California to supply over a third of the new air-conditioning load projected for the next decade. Fewer BTUs per kWh also means reduced air emissions, a feature that can contribute significantly to our environmental quality. ■

Mark MacCracken is the chair of the USGBC and CEO of CALMAC Manufacturing Corporation, the largest manufacturer of Thermal Energy Storage equipment, with more than 4,000 installations in 35 countries. In his more than 30 years with CALMAC, MacCracken has been involved in all aspects of the company including R&D, contracts, patents, manufacturing, marketing and finance. He was the Principal Investigator on research projects with Oak Ridge National Labs, NASA & National Renewable Energy Research Lab. In his continual support of energy efficiency, he is regularly in contact with the DOE, EPA, EPRI & electric utilities around the world.