U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Combined Heat and Power Technology Fact Sheet Series

Thermal Energy Storage

Thermal energy storage (TES) technologies heat or cool a storage medium and, when needed, deliver the stored thermal energy to meet heating or cooling needs. TES systems are used in commercial buildings, industrial processes, and district energy installations to deliver stored thermal energy during peak demand periods, thereby reducing peak energy use. TES systems are often integrated with electric or absorption chillers to reduce peak electricity costs and, in the case of new construction, to reduce capital costs by optimizing chiller size. Rightsizing equipment improves overall efficiencies for heating or cooling plants, thereby reducing total energy use and carbon dioxide (CO_2) emissions. TES technologies can support sites that have either renewable or fossil power generation, including combined heat and power (CHP) installations. With CHP, TES can help optimize equipment size by reducing the required peak CHP thermal capacity and increasing annual CHP usage. TES can also provide turbine inlet cooling for gas turbines used in CHP applications, which increases power production in hot ambient conditions.

Applications

TES is used in residential, commercial, and industrial applications. The technologies have been designed into thousands of energy systems, ranging from relatively large district heating and cooling applications, to smaller systems that deliver thermal energy for industrial processes and commercial buildings, to specialized applications such as turbine inlet cooling, to small residential floor heating systems.

This fact sheet is focused on TES used in CHP applications. For CHP sites, thermal energy can be stored in various forms for cooling (collectively referred to as "Cool TES") or stored as hot water for heating.

The 40,000 ton-hour low-temperature-fluid TES tank at Princeton University provides both building space cooling and turbine inlet cooling for a 15 MW CHP system.[1]
Photo courtesy of CB&I Storage Tank Solutions LLC

Cool TES

Cool TES technologies can be used with CHP systems and absorption chillers to provide additional building space conditioning during high demand periods when utility electricity tends to be most expensive. Cool TES technologies remove heat from an energy storage medium during periods of low cooling demand, or when surplus renewable energy is available, and then deliver air conditioning or process cooling during high demand periods. The most common Cool TES energy storage media are chilled water, other low-temperature fluids (e.g., water with an additive to lower freezing point), ice, or some other phase change material.

Cool TES technologies shift electricity use by decoupling chiller operation from instantaneous loads. By storing cooling capacity, Cool TES technologies can meet the same cooling demand as a non-storage system during a given period, but with a flatter electricity profile and smaller peaks. Cool TES technologies allow chillers to be sized more closely to the average load rather than the peak load, thereby reducing chiller size and capital cost. Some Cool TES technologies yield further cost reductions by enabling the use of lower water temperatures and higher air differential temperatures, thereby facilitating the use of smaller water and air distribution equipment.

1 "The Princeton Energy Plant," Princeton University Facilities, accessed December 2019, *https://facilities.princeton.edu/news/the-princeton-energy-plant*

This 8.8-million-gallon chilled-water TES tank provides 75,000 ton-hours of cooling, integrated with 45 MW CHP at Texas Medical Center in Houston.[2] Photo courtesy of TECO

Cool TES technologies provide advantages to both facilities and utilities. For sites, TES helps reduce energy costs (through load shifting) and equipment costs (through equipment size optimization). For example, many office buildings have air conditioning loads during the day that are two or more times above their average load.[3] The technologies can be integrated into microgrids to help balance cooling supply and demand. Cooling backup can be made available to sites that rely on intermittent renewable resources such as wind and solar. Utilities also benefit when customers implement Cool TES technologies, as they help alleviate strain on the grid by reducing peak electricity demand. Peak load management can help utilities defer or avoid expensive generation, transmission, and distribution system upgrades.

Ice storage integrated with CHP provides 23,400 ton-hours of cooling at the University of Arizona in Tucson.[4]
Photo courtesy of CALMAC

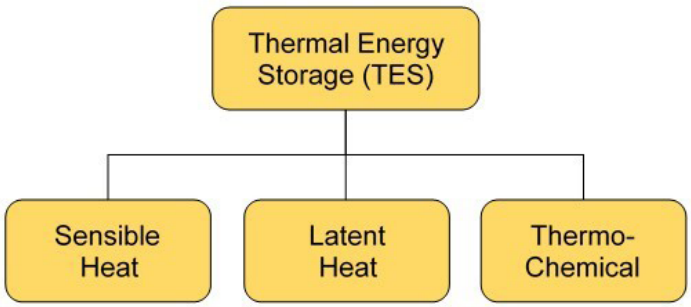
Hot Water TES

Hot water tanks are frequently used to store thermal energy generated from solar or CHP installations. Hot water storage tanks can be sized for nearly any application. As with chilled water storage, water can be heated and stored during periods of low thermal demand and then used during periods of high demand, ensuring that all thermal energy from the CHP system is efficiently utilized. Hot water storage coupled with CHP is especially attractive in cold northern climates that have high space heating requirements.

A CHP system with hot water storage is likely to have a significantly lower cost—and more potential applications—than a CHP system that stores chilled water produced from an absorption chiller. However, displacing hot water may provide fewer economic benefits than displacing chilled water, which is typically supplied by electric chillers, often during periods of high electricity prices.

Technology Description

TES technologies are often grouped into three categories: 1) sensible heat (e.g., chilled water/fluid or hot water storage), 2) latent heat (e.g., ice storage), and 3) thermo-chemical energy.[5] For CHP, the most common types of TES are sensible heat and latent heat.



TES can be grouped into three categories.

The following sections are focused on Cool TES, which utilizes chilled water and ice storage. Several companies have commercialized Cool TES technologies, driven by the economic benefits of reducing peak electricity demand, minimizing operating and capital costs for building air conditioning equipment, and increasing power output though turbine inlet cooling.

2 "Recovery Act Case Study: Combined Heat and Power System Enables 100% Reliability at Leading Medical Campus," U.S. Department of Energy, 2013. *https://www.energy.gov/sites/prod/files/2013/11/f5/teco_chp__recoveryact_casestudy.pdf*

3 J. Glazer, *Design Guide for Thermal Storage*, ASHRAE, 2019.

4 "University of Arizona," CALMAC Installations case study, accessed December 2019, *http://www.calmac.com/large-energy-storage-project-university-of-arizona*

5 I. Sarbu and C. Sebarchievici, "A Comprehensive Review of Thermal Energy Storage," *Sustainability* 10 (January 2018), 10.3390/su10010191.

Sensible Heat: Chilled Water

Several design variations have been used for chilled water systems, as listed in **Table 1**, but all work on the same principle: storing cool energy based on the heat capacity of water (1 Btu/lb-°F). Stratified tanks are by far the most common design. In these systems, colder water remains at the bottom, and warmer, lower-density water remains at the top. During times of peak cooling demand, the cooler water flows out the bottom and is integrated into the cooling system, leaving warm water in the tank. During off-peak hours, the warm water exits the tank at the top and runs to the chiller. Chilled water systems typically store supply water at 39°F to 42°F, which is compatible with most water chillers and distribution systems. Return temperatures are typically in the range of 55°F to 60°F or higher. Stratified low-temperature-fluid TES systems operate similarly but with lower supply temperatures, typically between 29°F and 36°F.

The 24,000 ton-hour thermally stratified chilled water TES tank is integrated with the 45 MW CHP system at Texas A&M University.[6] Photo courtesy of CB&I Storage Tank Solutions LLC

Table 1. Chilled Water Technologies[7]

Thermally Stratified	A thermally stratified tank is the most common design used for chilled water (or chilled fluid) TES. Thermal stratification relies on the density difference between the cool supply water (high density, bottom of tank) and the warm return water (low density, top of tank) to maintain separation of the two temperature zones with no physical barrier. The separation zone is characterized by a sharp temperature gradient, or thermocline.
Membrane or Diaphragm Separation	This design uses a flexible membrane to separate the cool supply water and the warm return water. The membrane, or diaphragm, moves up and down during charging and discharging. This design is prone to mechanical problems such as jamming of the diaphragm.
Empty Tank	A simple empty tank configuration consists of two tanks: one to hold cool supply water and one to hold warm return water. In a two-tank design, both tanks need to be sized to hold the entire water capacity. Two-tank designs require more space and are more expensive than a single thermally stratified tank design. Multiple-tank designs have also been used.
Labyrinth Tank	Labyrinth tanks use multiple compartments in a horizontal configuration, with water flowing from cell to cell. Labyrinth tanks are most common in high-rise buildings that can incorporate the tanks in the foundation. A drawback of labyrinth tanks is that temperature mixing occurs between the warm return water and the cool supply water.
Baffle-and-Weir	These tanks consist of internal walls with water flowing over a wall to one cell, and then under a wall to the next cell. A drawback of baffle-and-weir tanks is that temperature mixing occurs between the warm return water and the cool supply water.

6 "Project Profile – Texas A&M University," U.S. Department of Energy, CHP Technical Assistance Partnership, May 2019, *https://chptap.lbl.gov/profile/225/TAMU-Project_Profile.pdf*

7 Technologies listed are a subset from B. Lindsay et al., "Evolution of Thermal Energy Storage for Cooling Applications," *ASHRAE Journal*, October 2019.

Latent Heat: Ice Storage

Most latent heat technologies use frozen water (ice) as the phase change material, although others have been employed (e.g., eutectic salts). These technologies store cool energy in the form of ice at 32°F; the ice absorbs heat during its phase change to water, with a heat of fusion of 144 Btu/lb. Ice storage systems require a charging fluid at temperatures of 15°F or more below the normal operating range of conventional cooling equipment for air conditioning. Depending on the storage technology, special ice-making equipment may be used, or standard chillers could be engineered for low-temperature operation. The heat transfer fluid may be the refrigerant itself or a secondary coolant such as water–glycol or some other antifreeze solution. **Table 2** shows ice storage technologies in common use today.

An 8,600 ton-hour ice-on-coil internal melt TES system supplements the traditional air conditioning at Rockefeller Center in New York City.[8] Photo courtesy of CALMAC

Table 2. Ice Storage Technologies[9]

Ice-on-Coil Internal Melt	Ice forms on the exterior surface of pipes or tubes submerged in a water tank. Cold water–glycol from chillers cools the pipes or tubes during off-peak periods. Warm water–glycol from cooling loads melts the ice from the inside out during on-peak periods. This system is one of the most common technologies used for ice storage.
Ice-on-Coil External Melt	As with the internal melt design, ice forms on the exterior surface of pipes or tubes submerged in a water tank. In an external melt design, however, warm return water from cooling loads flows through the tank to melt the ice by direct contact. This system is often used in district cooling applications, as it can provide a cooler supply temperature than internal melt systems.
Ice Harvester	Ice forms on an evaporator located above a water tank and is periodically dropped into the tank. Cold water is supplied from the tank, and warm return water is returned to the evaporator.
Encapsulated Ice	This design uses plastic balls filled with water. The balls are held in a tank, and the encapsulated water freezes and thaws as cold or warm coolant is circulated through the tank.
Ice Slurry	Water in a water–glycol solution is frozen into a slurry and pumped to a storage tank. When needed, the cold slurry is pumped to heat exchangers or directly to cooling coils to meet cooling demands.

Cool TES Benefits

Table 3 shows site characteristics that help maximize benefits from Cool TES. Most of the benefits are economic, although other benefits include resilience (e.g., backup cooling during a grid outage or unplanned chiller maintenance). While the benefits are focused on Cool TES, some site characteristics also apply to hot water TES. For example, in the case of new construction or plant expansion, hot water storage can cost substantially less than a new boiler. Also, if CHP is being considered or is in use, including hot water storage can allow for optimal CHP equipment size by reducing the peak thermal output required.

Economics

The economic feasibility of Cool TES installations depend on capital costs, available incentives, and reduced electricity costs. Secondary benefits can include increased redundancy, reliability and resilience for cooling loads, and water storage for fire protection.[10]

Capital costs for a CHP installation with TES depend largely on the amount of chiller downsizing resulting from the TES; the total installation cost may be either higher or lower than that of a non-storage installation. In applications that are especially favorable for Cool TES, the facility can install smaller, less

8 "Rockefeller Center," CALMAC Installations, accessed December 2019, *http://www.calmac.com/energy-storage-case-study-rockefeller-center*

9 Ibid.

10 Adapted from J. Glazer, *Design Guide for Thermal Storage*, ASHRAE, 2019, Section 1.4.

Table 3. Site Characteristics that Contribute to Cool TES Benefits[11]

Site Characteristic	Benefit
Maximum cooling load significantly higher than average load	Cool TES technologies reduce electricity costs by minimizing peak loads and shifting loads to lower-cost time-of-use periods.
High demand charges or a large difference between on- and off-peak electricity prices	
New construction, plant expansion, or rehabilitation of an existing cooling system	Adding TES can cost much less than installing equivalent new chiller plant capacity.
Electric service at capacity	Cool TES can help avoid upgrade costs for transformers and switchgear.
Critical cooling loads	Cool TES can provide backup cooling to data centers, hospitals, and other mission-critical cooling applications.
CHP being considered or in use	Cool TES technologies flatten load profiles and help optimize CHP equipment size, economics, and operating efficiency.
Renewable power being considered or in use	Renewable power use can be maximized by charging Cool TES when excess electricity is generated.
Combustion turbine used in hot climate	Cool TES can be used for turbine inlet cooling to increase power generation in hot ambient conditions.

expensive chillers and balance-of-plant equipment, lowering the total capital cost. Cool TES technologies often allow wider water temperature differentials than typical non-storage systems, thereby reducing the size and cost of pumps and piping systems. Ice storage and low-temperature-fluid TES technologies can reduce supply air temperatures, decreasing the cost of water and air distribution systems.

For chilled water TES, the storage tank is typically the single largest cost. The installed cost for chilled water tanks typically ranges from $100 to $200 per ton-hour,[12] which corresponds to $0.97 to $1.95 per gallon based on a 14°F temperature difference (unit costs can be lower for exceptionally large tanks). Costs decline as capacity increases but can vary significantly based on the design temperature difference, tank material, shape, insulation, foundation design, site soil conditions, local labor costs, and special aesthetic considerations.

A key driver for TES in general is the avoided capital investment in conventional (non-TES) chiller plant capacity at times of new construction, retrofit expansions, or retirement of aging equipment. Cool TES generally reduces the required investment in conventional chilling equipment by allowing it to be sized to the average cooling load. For those situations, TES can achieve a rapid payback and possibly an immediate net capital cost saving.

Incentives, if available, improve Cool TES economics. Many utilities offer incentives for Cool TES technologies in the range of $200 to $1,000 per kilowatt of on-peak demand reduction. These incentives can significantly reduce installed capital costs, thereby reducing the payback period and strengthening the financial return of a TES system.

Reduced electricity costs are another major driver for Cool TES installations. Utility rate schedules often include higher rates for electricity purchased during peak summer hours when air conditioning loads are highest; Cool TES can offset these costs. The savings due to TES depend on site-specific electricity consumption profiles and utility rate schedules (i.e., the demand charge and the difference between on-peak and off-peak energy charges). ■

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

For more information, visit: energy.gov/CHP/
or email us at: CHP@ee.energy.gov

DOE/EE-2253 · September 2020

11 Adapted from J. Glazer, *Design Guide for Thermal Storage*, ASHRAE, 2019, Section 1.3.

12 J. Glazer, *Design Guide for Thermal Storage*, ASHRAE, 2019, Section 5.10.