Thermal Energy Storage

A Concise Overview[1]

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1. Introduction

Thermal energy storage (TES) helps offset the mismatch between periods when thermal energy (heat or cold) is available and in demand. TES offers the possibility of storing thermal energy for later use in its original form, or in conversion to electricity or other energy products.

TES has a wide variety of uses, most of which involve heating and cooling applications. Examples of TES are the storage of ground or solar energy for overnight heating, of summer heat for winter use, of winter ice for space cooling in summer, and of the heat or cool generated electrically during off peak hours for use during subsequent peak demand hours. Space heating using electric TES has been used extensively. District heating and cooling systems often also incorporate TES and can benefit from its careful integration into the overall system.

TES systems can yield significant benefits, which vary by application:

- **Increase efficiency**. By storing heat (e.g., waste heat, solar energy) or cold so that it can be used when needed, with temperature enhancement where necessary via heat pumps or other technologies, the efficiencies of heating and cooling operations can be increased.
- **Facilitate use of intermittent energy sources.** TES can facilitate the use of energy sources which are not available continuously, by storing energy between periods of availability and demand. Intermittent energy sources include renewables like solar and wind, as well as waste heat. TES thereby allows intermittent energy sources to meet a greater fraction of the loads for which they are intended.
- **Increase generation capacity**. Since demands for heating, cooling or electricity are seldom constant over time, the excess generation capacity available during low-demand periods can be used to charge a TES in order to increase the effective generation capacity during high-demand periods. This benefit allows smaller production units to be installed, or increased capacity to be attained without purchasing additional units.
- **Shift energy use to low-cost periods.** TES allows energy consumers subject to time-of-day pricing to shift energy purchases from high- to low-cost periods.
- **Improve operation of heat pumps.** By providing hot or cold reservoirs, TES systems can complement heat pumps, for heating or cooling, and improve system efficiencies and performances.
- **Improve operation of cogeneration plants.** Cogeneration plants are generally operated to meet the demands of the connected thermal load, which often results in excess electric generation during periods of low electricity demand. With TES, a cogeneration plant need not follow a load and can be operated more advantageously.
- **Reduce environmental impact.** By increasing the efficiency of systems which utilize TES and facilitating the use of renewable energy sources and waste energy, TES systems help reduce emissions of pollutants and environmental impacts.

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[1] This document was prepared in March 2008 by Marc A. Rosen, Ph.D., P.Eng., Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, for the Canadian GeoExchange Coalition. This analysis is part of a broader CGC project aimed at incorporating thermal energy storage guidelines in the CGC training programs.

- **Save money.** Many of the above benefits allow TES systems to provide significant financial gains over their lifetimes.

TES can allow thermal equipment to operate more effectively, flexibly and economically, and can facilitate large scale substitutions of energy resources. TES is a great fit for heat pump systems.

2. Types of thermal energy storage

Thermal energy may be stored by elevating or lowering the temperature of a substance (i.e. altering its sensible heat), and/or by changing the phase of a substance (i.e. altering its latent heat). Consequently, there exist two main TES categories: sensible (e.g. water, rock, soil) and latent (e.g. water/ice, salt hydrates). In either case, the selection of a TES system mainly depends on such factors as the application, the storage period required, economics, operating conditions, etc.

A TES generally consists of a storage medium, a container, and equipment for injecting and recovering thermal energy. The container retains the storage material and prevents losses of thermal energy.

2. 1 Sensible thermal energy storage

Sensible TES systems undergo changes in sensible heat, which are associated with temperature change. Some of the more common types of sensible TES follow:

- **Tank/container.** Tanks and containers filled with a heat, storage medium, such as water or rock, can act as a TES. Such tanks are often made of steel or concrete because of their physical characteristics, cost, availability and easy processing.

Ceramic bricks can also act as a good Ceramic bricks can also act as a good heat storage medium, especially for uses in new and old buildings, where they are advantageous due to their modular sizes, ease of installation and high heat-retention abilities.

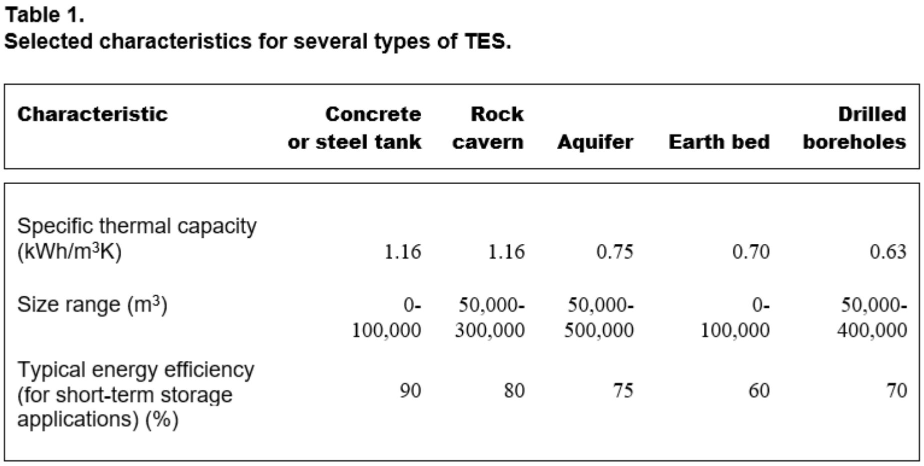

Table 1.
Selected characteristics for several types of TES.

Characteristic	Concrete or steel tank	Rock cavern	Aquifer	Earth bed	Drilled boreholes
Specific thermal capacity (kWh/m^{3}K)	1.16	1.16	0.75	0.70	0.63
Size range (m^3)	0-100,000	50,000-300,000	50,000-500,000	0-100,000	50,000-400,000
Typical energy efficiency (for short-term storage applications) (%)	90	80	75	60	70

Sources:
Guide to Seasonal Storage, Swiss Federal Energy Office, July 1990.
Piette, M.A. Learning from Experience with Diurnal Thermal Energy Storage Managing Electric Loads in Buildings, CADDET Analysis Support Unit, June 1990.

- **Earth bed.** Heat or cold can be transferred into underground soil for storage and subsequent recovery. The use of earth as a TES medium is often restricted to new construction, since the application requires installations in the ground, beneath a structure making retrofit work difficult.

- **Aquifer.** An aquifer is a groundwater reservoir, in which the water is located in impermeable materials such as clay or rock and moves very slowly. An aquifer TES is typically a permeable, water-bearing rock formation. Aquifers often have large volumes, exceeding millions of cubic meters, and consist of about 25% water. In aquifer TES, water from the aquifer is extracted, and heated or cooled. It is then reinjected at another point in the aquifer for storage and subsequent recovery. With an aquifer system, therefore, two well fields are often tapped: one for cold storage and the other for heat. Aquifer stores are most suited to high capacity systems. External thermal energy is stored in some aquifer TES systems, while the natural groundwater temperatures are used in others.

• **Borehole.** A network of tubes inserted into boreholes drilled into the earth can be used as underground storage, allowing heat or cold to be transferred into underground soil and rock for storage and subsequent recovery.

• **Rock cavern.** A rock cavern can be filled with a storage medium and used as a TES. The storage medium in such systems depends on the ability of the cavern to hold it. Such TES systems are usually large.

• **Solar pond.** A salinity gradient solar pond is an integrated collection and storage device of solar energy. In an ordinary pond, the sun's rays heat the water which, being less dense, rises to the surface and loses heat to the atmosphere. A solar pond inhibits this phenomenon by dissolving salt into the bottom layer of the pond, making it too dense to rise to the surface, even when hot. The salt concentration increases with depth, forming a salinity gradient. Sunlight which reaches the bottom of the pond remains trapped there as thermal energy. Useful thermal energy is recovered as hot brine.

Note all of the above types of TES are in-ground systems. Tank-based TES can be located in or above ground. Note also that both hot and cold TES can utilize the above TES categories.

Selected TES system characteristics are compared in Table 1 for several types of TES. The sizes range to as large as 500,000 m^3, while the efficiencies vary, for short-term applications, from approximately 60 to 90%. The specific thermal capacity is the storage capacity per unit volume and per unit temperature rise, and allows comparisons of storage capacity for TESs of the same size and same temperature increase.

Sensible heat storage systems commonly use rocks or water as the storage medium due to their availability, cost, ease of use and thermal characteristics. The high heat capacity of water often makes water tanks a logical choice for TES systems that operate in a temperature range needed for building heating or cooling. The relatively low heat capacity of rocks and ceramics is somewhat offset by the large temperature changes possible with these materials, and their relatively high density.

Sensible TES can be applied to a wide range of storage duration. Long term (daily to weekly) systems often use crushed rock beds, earth beds, water tanks, ceramic brick and building mass. Long term (as long as seasonal) TES often utilize rock beds, earth beds and water tanks. Aquifer TES can be used for storage periods ranging from daily to seasonal.

Some sensible TES systems are designed to take advantage of thermal stratification, the existence of a temperature gradient across the storage. Thermal stratification is desirable as it avoids loss of temperature due to mixing, and is simpler to achieve in solid storage media than in fluids.

2.2 Latent thermal energy storage

Latent heat changes are the heat interactions associated with a phase change of a material, usually from a solid to a liquid and back. Latent heat TES systems store thermal energy as a material changes phase at constant temperature.

The latent heat change during phase change is usually much higher than the sensible heat change for a given medium. Thus, latent TES has a high energy storage density. Latent heat TES systems also incorporate a storage containment and heat exchange capability for transferring thermal energy into and out of the storage.

Latent heat TES systems utilize a variety of materials as storage media. The storage medium is usually selected so that it undergoes a phase transition within the desired operating temperature range. Latent storage media often include phase change materials, including inorganic materials, organic materials, large fatty acids, aromatics. Salt compounds that absorb a large amount of heat during melting (e.g., eutectic salts, salt hydrates, Glauber's salt) are useful for latent TES. Paraffin waxes are another common phase change material since they exhibit high-stability and little degradation over repeated cycles of latent TES operation.

The phase change material in a latent heat TES can be contained in a single large vessel, or in rods or plastic envelopes. These small modules in the latter case, and the small number of modules required for storage, make latent TES especially suitable and convenient.

Latent heat TES can be used to store thermal energy at hot or cold conditions. Cold TES often utilizes latent heat changes, using such storage media as water/ice, eutectic salts, glycol, brine and ice slurry.

3. Design and operation of thermal energy storage

All TES systems are designed to operate on a cyclical basis (usually daily, weekly or seasonally). Energy demands in the commercial, industrial, utility and residential sectors, for such tasks as space and water heating, cooling and air conditioning, vary on daily, weekly and seasonal bases. A TES is selected to match the application. Numerous other criteria also affect the selection of TES systems, including technical factors (e.g., required storage capacity, storage duration, physical size, space availability, efficiency, installation limitations, reliability, safety, impact on performance of the overall application), environmental factors, and economics (e.g., system cost, lifetime, payback period). Appropriate trade-offs are often made among competing criteria.

ln considering TES operation, it is useful to characterize TES systems according to storage duration.

Short-term (or diurnal) TES addresses peak loads lasting a few hours to a day in order to reduce the sizing of systems and/or to take advantage of energy-tariff daily structures, or to allow intermittent energy sources to be used throughout the day. The use of diurnal TES for electrical load management in buildings is increasing. TES allows electricity consumption costs to be reduced by shifting electrical heating and cooling loads to periods when electricity prices are lower, usually during the night. Load shifting can also reduce demand charges, which can represent a significant proportion of total electricity costs for commercial buildings.

Medium-term TES operate on weekly cycles, and exhibit many of the characteristics of short-term systems.

Long-term TES operates on annual or seasonal cycles, and usually take advantage of seasonal climatic variations. Seasonal TES systems have a much greater capacity than daily TES, often by two orders of magnitude. Thermal losses are more significant for long-term storage, so more effort is made to prevent thermal losses in seasonal rather than daily TES. While diurnal systems can generally be installed within a building,' seasonal storage requires such large storage volumes that special care is required in locating the storage and separate locations are often required.

ln cold TES applications, several strategies are available for charging and discharging so as to meet cooling demand during peak hours. The main strategies are full storage and partial storage. A full-storage strategy shifts the entire peak cooling load to off-peak hours, a strategy that is most attractive when peak demand charges are high or the peak period is short. With partial-storage, the chiller operates to meet part of the peak-period cooling load, and the rest is met by drawing from storage. Partial-storage systems are therefore load leveling and demand limiting

Energy quality as measured by the temperatures of the materials entering, leaving and stored within a storage is an important consideration in TES. For example, 1 kWh can be stored by heating 1,000 kg of water 0.86°C, or by heating 10 kg of water 86°C. The latter case is more attractive in terms of energy quality as a wider range of tasks can be accomplished with the higher temperature medium upon discharging the storage. But the costs of TES systems that retain thermal energy quality are often higher than for those that do not.

4. Use of thermal energy storage with heat pump technology

The heat pump is an important component of many energy efficiency and conservation strategies. TES can be used beneficially in conjunction with heat pump technology, for heating and cooling applications.

4.1 Cooling applications

Combining of a heat pump and a cold TES can provide the following benefits:

- **Load levelling of electricity demand for air conditioning.** Cold TES can shift peak air conditioning loads to the night, increasing significantly the annual dependence on night time electricity. A typical cold TES, for instance, shifts half the air conditioning load to the night on the peak day, and permits the annual dependence on night time electricity to reach up to 70% for cooling and 90% for heating. Also, a cold TES system can improve the annual load factor of electricity generation facilities, and save money for consumers when electric power companies provide discount rates for night time electricity.

- **Efficient operation of heat pumps.** Although a heat pump typically achieves maximum efficiency at a certain operating condition, heat pump operation normally can not be maintained at the most efficient condition in commercial and residential applications because cooling and heating loads vary temporally. This variation reduces the seasonal efficiency of heat pumps. Because heat pumps integrated with cold TES can operate independently of the cooling and heating load of buildings, cold TES helps avoid this problem by permitting operation of heat pumps at the most efficient operating condition.

- **Reduced heat pump size.** For a fixed air conditioning load, the longer operating hours of a heat pump integrated with cold TES allow a smaller capacity heat pump to be used, reducing electrical demand peaks and decreasing initial and operating costs.

Heat pumps can be beneficially integrated with both latent and sensible TES for cooling. In the former case, heat pumps can be combined with latent TES using ice and ice slurry. An example of the latter case is a system combining water-based cold TES combined with heat pumps, which can make heat pump operation more economic and help level electrical loads. In conventional air conditioning using heat pumps, the heat pumps operate during the day when cooling demand exists. This operation contributes to electricity daytime demand, which is significant since cooling demand is sometimes responsible for more than one-third of peak electrical demand. In a typical water-based cold TES system, half of the daily cooling load can met by night operation of heat pumps.

4.2 Heating applications

Combining of a heat pump and TES for heating applications can provide numerous benefits. Two sample systems are considered here.

Heat from solar collectors, which is often used directly for space heating, can instead be used as a heat source for a heat pump. In such a solar-augmented heat-pump system, the solar-collector outlet tempera-tures can be lower than with direct heating, increasing energy efficiency and reducing the cost of the solar collector.

The higher source temperature also increases the coefficient of performance of the heat pump, reducing its electricity consumption. Such a system can operate in various modes. With small TES, the solar collector improves heat-pump efficiency mainly during sunny periods. With larger TES, the solar energy provides a warm storage for heat-pump operations during cloudy periods and night. Alternatively, the overall system can be designed so that the heat pump operates only during off-peak hours. Such an approach requires two TESs, one to store solar energy and one to store the heat-pump output for space heating at all times.

Heat pumps can be combined with latent TES in innovative configurations. For example, a heat pump can use a latent TES to enable rapid room temperature increases and defrosting. In one such system, the latent TES uses polyethylene glycol as a phase change material, which surrounds a rotary compressor of the air-conditioner/heat pump for a room. Heat released from the compressor is transferred to the TES through a finned-tube heat exchanger, and recovered for use during start-up and for defrosting. During start-up, the TES halves the time to reach a 45°C discharge air temperature. The integration improves heat capacity by about 10% and coefficient of performance by 5%, and requires the same installation space as a conventional heat pump/air conditioner.

4.3 Heating and cooling applications

Heat pumps can be advantageously integrated with TES for combined heating and cooling operations, particularly for multi-season applications.

For example, a heat pump and an aquifer TES allows cold water to be extracted from a cold well during summer and warmed by cooling a building, and then returned to a warm well in the aquifer. A heat pump can cool the cold water further, if necessary. The warmed water increases the temperature of the aquifer near the warm well. The operation is reversed during winter, with warm water extracted from the warm well and boosted in temperature by the heat pump if necessary.

With a ground source heat pump with seasonal TES, the ground or groundwater is cooled during heating, as heat from the TES is supplied to the building. After the heating season, the stored cold is used for direct cooling, via cold groundwater from the injection well or cold brine from earth heat exchangers. After some time, the ground temperature may be too high for direct cooling. The system then can be operated as a conventional heat pump, cooling the building space and storing heat in the ground until the next heating season.

5. Economic assessments

The economic justification for TES systems normally requires that the annualized capital and operating costs be less than those required for primary generating equipment supplying the same service loads and periods. In general, TES systems accrue fuel cost savings relative to primary generating equipment, but often at the expense of higher initial capital costs.

TES cost-effectiveness is often evaluated considering the distribution of heating, cooling and electrical loads over time, TES system characteristics (e.g., size) and performance (e.g., control methods, efficiency), and economic factors (e.g., electricity demand charges, time-of-use costs, TES costs, financial incentives). Economic evaluation and comparison criteria often include simple payback period, return on investment, and comparisons of the annualized investment cost with annual energy cost savings. Financial analyses of TES systems are important since they sometimes have relatively high initial capital costs which are justified through savings over time.

Heating TES systems can be justified economically for most facilities which have significant space heating needs and are billed under time-of-use electric rate schedules that have large differentials between peak and off-peak electric consumption.

Cooling TES systems are generally advantageous for new facilities which have cooling loads that are large in the day and small at night. For retrofit situations, cooling TES is sometimes difficult to justify unless the cooling system is being replaced because of old age or inadequate capacity.

TES systems can be cost-effective in both residential and commercial buildings, with projects often having payback periods of less than three years. Payback periods for cold TES systems, vary significantly with application, from less than one year to over ten years in some instances. The economic feasibility of TES can be influenced by incentive programs (e.g., rebates, special electricity rates, tax incentives) from governments, electrical utilities and other agencies.

TES systems can shift nearly all energy use for space heating to off-peak hours, whereas only about 50% of the energy for heating is used during off-peak periods in conventional systems. The Electric Power Research lnstitute indicates that overall HVAC operating costs can be lowered by 20-60% by combining TES with cold-air distribution. TES systems for cooling capacity have been most successful in larger buildings, although the attractiveness of applications in smaller units has been increasing.

For TES systems designed to reduce electricity costs, TES allows consumer electricity costs to be reduced by shifting electrical loads to periods of lower electricity prices when time-of-use tariffs exist. Shifting or spreading of the load can also reduce demand charges significantly. Benefits from TES also accrue to electricity utilities, since shifting electrical loads to off-peak periods reduces peak demands and required generation capacity, and reduces the utilization of more expensive and often more polluting generating stations. Hence utilities often offer rebates for TES.

TES applications have achieved various levels of market penetration, depending on country. Diurnal heat storage has achieved a large market share in many countries. Diurnal cold storage in air conditioned buildings for demand-side management is growing. Short-term cool TES for air conditioning is often cost-effective, with numerous applications in the USA, Canada, Japan and Europe. lndividual houses or commercial buildings can use diurnal TES either for heating or cooling applications. Seasonal TES has achieved the greatest success in northern countries, sometimes in conjunction with district heating. Large seasonal TES has often been installed with solar collection systems in large buildings or in association with district heating.

ln the future, TES is expected to be able to reduce the capacity of heating and cooling systems by 50-70%, and to yield energy savings due to better system efficiencies.

6. Closing remarks

Much TES technology has reached a high level of maturity and has established markets. Although many types of TES have been demonstrated and are commercially available, advances to the technology are continually being made and new types of TES are under development. TES is expected to be increasingly applied as new energy technologies are developed, and to contribute to solving the problems societies face regarding energy supply, environmental impact and overall sustainability. ●

References and useful readings

Standard 943: Method of Testing Active Sensible TES Devices Based on Thermal Performance, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, Georgia, 2000. (ASHRAE provides testing standards for TES systems. This sensible TES standard is the second half of a revision of ASHRAE's first TES standard, 94-77: Methods of Testing Thermal Storage Devices Based on Thermal Performance. The first half was issued as ANSI/ASHRAE 94.1-1985: Method of Testing Active Latent Heat Storage Devices Based on Thermal Performance.)

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Design and Installation of Underground Thermal Energy Storage Systems for Commercial and Institutional Buildings. Canadian Standards Association. C448.3 Series-02, 2002.

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Paksoy, H.O., Ed. Thermal Energy Storage for sustainable Energy Consumption: Fundamen¬tals, Case Studies and Design. NATO Science Series II: Mathematics, Physics and Chemistry, Vol. 234, Springer, New York, 2007. (This book presents research on using natural and renewa¬ble energy resources with thermal energy storage in heating and cooling applications and covers many aspects of thermal energy storage in aquifers, boreholes, phase change materials and thermochemical reactions. Climate change mitigation with thermal energy storage is also covered, as are site investigations for underground thermal energy storage applications. Borehole thermal energy storage design examples using Earth Energy Design software are provided.)

International Energy Agency (IEA), http://www.iea.org (IEA acts as energy policy advisor to member countries in their efforts to ensure reliable, affordable and clean energy for their citizens, and has much documentation on TES.)

IEA Heat Pump Centre, http://www.heatpumpcentre.org (This Centre is an international information service for heat pumping technologies, applications and markets. The goal is to accelerate the implementation of heat pumps and related heat pumping technologies including air conditioning and refrigeration. The Centre publishes the IEA Heat Pump Center Newsletter, which often has articles on thermal energy storage.

Energy Conservation through Energy Storage Implementing Agreement (ECES IA), International Energy Agency, http://www.iea-eces.org. (This site has information on thermal energy storage. In addition IEA has held conferences on thermal energy storage within the framework of this implementing agreement since 1981, and the proceedings of these conferences contain valuable information.)

National Renewable Energy Laboratory, U.S Department of Energy, Office of Energy Efficiency & Renewable Energy, http://www.nrel.gov. (This is the primary laboratory for renewable energy and energy efficiency research and development in the U.S. Its web site contains information on thermal energy storage.)

CANMET Energy Technology Centre (CETC), http:/twww.nrcan.gc.ca/es/etb/cetc. CETC is Canada's leading federal government science and technology organization with a mandate to develop and demonstrate energy efficient, alternative and renewable energy technologies and processes, including thermal energy storage.

University of Wisconsin-Madison HVAC&R Center, http://www.engr.wisc.edu/centers/hvac. (Thermal Storage is a feature of the web site, http://www.hvacr.wisc.edu/tsarc.htm. The Center was originally established in 1989 as the Thermal Storage Applications Research Center. The Center publishes the EPRI HVAC&R Center Quarterly Newsletter, which often has articles on thermal energy storage.)

Centre for Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), http://www.caddet.org. (This international information source helps managers, engineers, architects and researchers find out about renewable energy and energy-saving technologies that have worked in other countries)