3.171/3.371 Thermal Energy Storage System

Energy storage is a critical technology, since although electricity generation is relatively constant throughout time, the demand and need for electricity fluctuates daily and seasonally. Research have been conducted for centuries to increase the efficiency and lower the costs of such storage systems. Thermal energy storage (TES), a type of energy storage system, is a “technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation” (IRENA 1). Simply put, TES allows for thermal energy to be collected and stored for later use. TES has been of interest recently not only due to its ability to balance the supply and demand of energy sources, but because of its ability to increase the overall efficiency of storage, reduce the peak demand and therefore the associated costs, and reduce CO₂ emission and costs.

These developments allow for utilities and consumers to achieve energy demand balance, which can reduce costs, earn Green Building Certification, remove load from building demand, and address the main cause of electric utility grid stress. TES has gained much attraction recently as well, especially since it is increasingly being used as a demand response resource, acting as one of the main resources for making electric utility companies much more sustainable. In addition, TES has much potential in combination with solar power, of which installations have been increasing exponentially (IRENA). To fully understand whether TES is a
sustainable and long-term energy solution, technology behind TES, types of TES, costs and feasibility, barriers and limitations, and past case study projects will be thoroughly analyzed throughout this paper.

TES, which can be operated with chilled or hot water, stores thermal energy that is produced during periods of off-peak electrical demand. The thermal energy is then stored in a thermal energy storage tank. This energy can then be withdrawn and distributed as needed during peak periods through water entering and exiting via diffusers located at the top and bottom of the tank. This process locates the colder and denser water to the bottom of the tank, while the warmer water is made to move towards the top. As the tank discharges, the associated equipment are de-energized, and the water is circulated for cooling, as is illustrated in Figure 1. After this process, the tank will now contain warm water and be ready for be in “charging” mode. This mode refers to warm water being “withdrawn through the top diffuser, sent to the chiller plant, and then returning cold into the tank through the bottom diffuser after being cooled by a chiller system” (Frankenfield). After these two phases, one thermal energy storage cycle has ended, and this process repeats continuously.
With these main characteristics governing the process, there are four main types of thermal energy systems currently on the market: sensible thermal energy storage, underground thermal energy storage, phase change materials, and thermal energy storage via chemical reactions. These three systems differ in capacity, power, efficiency, storage period, charge and discharge time, and cost. These properties are inherently linked, with capacity, power, and discharge time being interdependent variables. Each of these factors will be analyzed to gain further insight on the feasibility of the different types of TES.

Sensible thermal energy storage is one of the most well-known types which utilizes hot water tanks to save energy in water heating systems using “solar energy and co-generation energy supply systems” (IRENA 6). These types of water tank storage have been proven to be cost-effective, and recent research has increased the efficiency as well by ensuring an optimal water stratification and highly effective thermal insulation. In addition, hot water storage systems these types of hot water storage systems have also been used as a buffer storage for hot water supply and in solar thermal installations in combination with building heating systems. These are especially effective for thermal energy storage with seasonal fluctuations in mind. For this purpose, the systems have volumes of several thousand cubic meters and charging temperatures in the ranges of 80-90°C (6).

Underground thermal energy storage (UTES), as the name suggests, utilizes the underground for heat and cold storage. Main types of UTES technologies include borehole storage, aquifer storage, cavern storage, and pit storage. The decision on the type of UTES is
heavily dependent on the local geography (IRENA 7). Borehole storage uses vertical heat exchangers that are installed underground to allow for the transfer of thermal energy to and from the ground layers. Aquifer storage utilizes natural underground water-permeable layer for storage, with thermal energy transferred via mass transfer. Cavern storage and pit storage use “underground water reservoirs created in the subsoil to serve as thermal energy storage systems” (IRENA 8). These two types, although are technologically feasible, are not often utilized due to the high investment costs.

In contrast with sensible heat storage with low energy density and variable discharging temperatures, phase changing materials (PCM)-based TES allows for “higher storage capacities and target-oriented discharging temperatures” (IRENA 8). Although the benefits are significant, penetration has been slow due to their high costs. For PCMs, the “change of phase could be either a solid/liquid or a solid/solid process” (8), but solid/liquid transitions are more commonly used because it is a more compact, efficient, and cost effective operating system. These types of processes can be utilized for both short-term daily and long-term seasonal energy storage. Most common and useful types of PCMs include ice, Na-acetate Trihydrate, Paraffin, and Erytritol.

Thermal energy storage via chemical reactions allows for high energy density systems. Reactions such as absorption or “adhesion of a substance to the surface of another solid or liquid” (IRENA 9) can not only store heat and cold like other TES, but also control for humidity. Due to this feature, thermal energy storage via chemical reactions is especially useful in hot and/or humid climates or confined spaces (9). During the charging process, water molecules are desorbed, and TES remains in this state until water molecules are all absorbed by the absorbent
and the TES is discharged. Since due to these chemical reactions, TES can store thermal energy with higher efficiency and then convert the heat into cold, the system has been increasingly attractive (9).

Although there are a variety of applications for TES systems and most chilled water district cooling systems can benefit from TES, the most important fields are in the building and industrial sectors. TES systems can be utilized both in centralized and distributed manners. In a centralized system, waste heat from industrial processes are stored in a centralized plant. Such a design allows for hundreds of kW to several MW of power. Distributed systems act as buffer storage systems. They store solar heat to be used in smaller, domestic scales, with power ranging to tens of kW. Both centralized and distributed systems have the capacity to improve the energy efficiency of their respective surroundings, whether it be industrial or residential. They are able to store waste thermal energy in a form that can be used at peak demand times. Additional industries including energy-intensive industrial sectors like cement, iron and steel, and glass productions and manufacturing industries can achieve significant benefits from integrating TES into their energy platforms. Government and military, hospitals and airports, universities, natural gas power plants, and data centers have benefited greatly from incorporation of TES as well.

Although not as much experimented with, TES can work well in combination with renewable energy resources as well. For solar energy systems, TES can act as “buffers for domestic hot-water production or to long-term heat storage for residential and industrial heating purposes” (IRENA 12). Wind energy and TES can work hand-in-hand as well. The efficiency of a “compressed energy storage can be improved from 50% to more than 70% by
storing heat during compression and discharging it to support expansion” (13). Cold storage systems can be charged using renewable electricity during solar or wind peak periods and the energy stored from such can be delivered to customers when the demand is high.

With widespread penetration being one of the main objectives, costs and feasibility are often just as important as the technology. To establish an accurate cost estimate, it is important to take the costs of “storage materials, technical equipment for charging and discharging, and operation costs” into account (IRENA 14). TES sensible heat system is relatively inexpensive with the storage media, which include water, soil, rocks, concrete, and molten salts, being of relatively low costs. The only main factor of concern is the storage material, which requires high levels of thermal insulation. In the past, the system consisting of “5,000-10,000 m³ water container with energy content between 70-90 kWh/m³ had investment costs between $55-220/m³, translating to specific investment costs from $0.53-$3.20 per kWh” (14). For UTES systems, boreholes and heat exchangers make up the majority of the cost structure. “Specific costs range from $0.12-11.00 per kWh and depend heavily on local conditions” (14).
Phase change material (PCM) and thermal energy storage via chemical reactions are the most expensive and complex of all. Enhanced heat and mass transfer technologies are needed to achieve the necessary storage capacity and power. With this taken into consideration, “the cost of a PCM system ranges between $17-80 per kWh” (IRENA 15). The cost can be even higher for specific types of PCM systems such as micro-encapsulated PCMs, which does not use heat exchange surfaces. “The cost of complete plaster board ($20/kg) with micro-encapsulated paraffin to be used as a passive cooling device within building structures includes the price of paraffin (about $9/kg) and the micro-encapsulated material ($18/kg)” (15). Currently, after an overall economic evaluation, PCM’s cost cannot be justified for ordinary usage, especially on a large commercial scale. PCM has gained much attention for clothing and small scale building construction, but expanding this production to a large construction scale will require many rounds of cost reduction.

As aforementioned, TES have a number of benefits. First of all, since peak-time electricity is so expensive (often 2 to 4 times more expensive than off-peak electricity of approximately 4 cents/kWh), an effective use of TES can provide significant cost savings, but for annual energy and operational costs. Secondly, incorporating TES can allow the buildings to become eligible for a recognized “green” building certification. Such certifications can allow for subsidies for the operating costs, as well as increase the resale value and occupancy. Additionally, thermal storage, especially for air-conditioning loads, is the main contributor to
electric utility grid stress. Since TES will be located at the buildings themselves, the burden will be removed from the electric grid itself. This will increase efficiency, as well as lower costs for all parties involved, and expand the cooling capacity at these existing buildings. These additions to the facilities can also allow owners to negotiate in both regulated and deregulated markets, because they are less dependent on the main grid system, and through demand response, can actually give back to the grid as well. Lastly, not only do TES provide high efficiency, it has the capability to recover up to 99% of the stored cooling. This level of efficiency is unparalleled by most of other energy storage systems available at this date (Silvetti).

Barriers and limitations, however, cannot be neglected to gain a full picture of the technology usage. In addition to the market entry difficulties and cost as previously discussed, material properties can be problematic. Many Research and Development projects nowadays are focusing on the properties of the materials of interest, especially the tolerable temperature ranges. Not only do each of the materials have to be evaluated, reacting materials must be taken into consideration as well, which makes the design much more complicated. TES market penetration has been challenging as well. Penetration has been around 1.3% per year for new constructions and 1.5% for renovations in developed countries. These values are expected to increase to 5% in the next decade, with much more interest expected from emerging economies, since these countries are pursuing higher rates of new building construction. Whether the penetration rate will increase to justify the R&D and other relevant costs cannot be determined with the current level of installations.

To put all of these theoretical analyses into perspective, TES project showcases are analyzed. One of the main examples are VA Medical Center in Dallas, TX. In 1996, the U.S.
Department of Veterans Affairs North Texas Health Care Systems constructed a 3.3 MG TES tank to save energy costs. This construction included TES with a capacity of 24,600 tons-hour of cooling for the 84 acre of health care campus with more than 2.5 million square feet of conditioned space. Since this construction, expansion of the medical center has increased the peak cooling load, further increasing the benefit of having a TES system for these summer peak demand periods. In addition, TES provides power-sensitive medical center the ability to react to emergency power outages, as well as to temporarily shut down the main power plant for routine maintenance without interruptions to the medical center services. For more than the past ten years, TES system have been operating without defect and have provided energy cost savings (Frankenfield).

Similar case can be witnessed in a thermal energy storage tank in Vicenza, Italy. To optimize energy usage in Dal Molin, a heavily populated area that was a former site of an Italian air base in Vicenza, the U.S. Army constructed a TES. The goal of the construction was to use different types of fossil fuels for electricity and heat generation, and thus reduce more than 42% of the annual costs. For this purpose, 0.435 MG, 3,920 ton-hour TES tank was constructed. Experiences that align with the two aforementioned with the construction of TES occurred throughout the globe, including in UT Pan Am TES Tank (Edinburg, TX), TES for Bucknell University (Lewisburg, PA), TES at San Antonio Airport (San Antonio, TX), and TES Tank for Semi Conductor Chip Manufacturer (Dallas, TX). Corresponding real life experiences associated with TES systems demonstrate the efficacy of these systems, rather than just being theoretical ideals.
Understanding of the technological backgrounds of TES, types of TES currently available for commercial use, costs of each of these types available, benefits, limitations, and past case studies are critical to determining short-term and long-term feasibility of the system. Due to TES penetration has been limited in both developed and emerging economies, TES will not be feasible in the short term in the mass commercial scale, but can be expected to grow and establish itself as a main form of energy storage in the long-term. This is due to the cost (especially for sensible heat systems and UTES) and sustainability benefits it provides over currently utilized nonrenewable technologies. To add to this, thermal energy storage is expected to grow hands in hands with solar energy. With solar energy projected to become the world’s largest source of electricity by 2050, TES is expected to grow significantly along with this innovation (SEIA). As the volume of production of the relevant equipment and level of penetration increases, the specific costs will be even lower than what was predicted earlier in the paper, which will encourage further installations. With the sustainable and cost effective nature of TES, in combination with the rapid expected growth of the solar energy market, TES is worthy of further research and support.
References


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