Building Thermal Energy Storage - Concepts and Applications

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BUILDING THERMAL ENERGY STORAGE – CONCEPTS AND APPLICATIONS

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Abstract

The use of Thermal Energy Storage (TES) in buildings in combination with space heating, domestic hot water and space cooling has recently received much attention. A variety of TES techniques have developed over the past decades, including building thermal mass utilization, Phase Change Materials (PCM), Underground Thermal Energy Storage, and energy storage tanks. In this paper, a review of the different concepts for building or on-site integrated TES is carried out. The aim is to provide the basis for development of new intelligent TES possibilities in buildings.

TES systems for cooling or heating capacity are utilized in applications where there is a time mismatch between the demand and the economically most favourable supply of energy. TES can provide short term storage for peak shaving as well as long term storage for the introduction of renewable and natural energy sources.

Sustainable buildings need to take advantage of renewable and waste energy to approach ultra-low energy buildings. Utilization of low-exergy heating and cooling sources requires that energy storage is integrated into sustainable building design. A coordinated set of actions for improved TES designs are needed if the potential benefits are to be fully realized. Well designed systems can improve building's energy efficiency and comfort level, yielding significant cost savings and promising payback period.

Keywords: thermal energy storage, ground storage, PCM, TABS, energy storage tanks

1 Introduction

Energy demands in commercial, industrial and residential sectors vary on daily, weekly and seasonal basis. These demands can be matched with the help of Thermal Energy Storage (TES) systems that operate synergistically and are carefully matched to each specific application.

The use of TES for heating and cooling applications has recently received much attention (Dincer, 2002 and 2011). A variety of new TES techniques have been developed over the past four decades. Well designed systems can reduce initial and maintenance costs and energy use and demand (Dincer, 1996 and 1997).

Thermal energy storage is the temporary storage of high- or low-temperature energy for later use. Different examples about the efficient utilisation of natural and renewable energy sources, cost savings and increased efficiency achievable through the use of TES could be considered.

In continental climates, it is possible to store heat from the warm summer months for use in winter, while the cold ambient temperatures of winter can charge a cold store to provide cooling in summer. This example of seasonal storage can meet the energy needs caused by seasonal fluctuations in temperature. Such a scheme requires great storage capacity because of the large storage timescales. The same principle can be applied on a small scale to smooth out daily temperature variations. For example, solar energy can be stored during the day and used for night heating. Another example is the use of thermal storage to take advantage of off-peak electricity tariffs. Chiller units can be used to cool a thermal storage at night, when the cost of electricity is relatively low. The storage then provides cooling for air conditioning throughout the day. In that way electricity costs are reduced, the efficiency of the chiller is increased and the peak electricity demand for supply utilities is reduced.

2 Benefits of Thermal Energy Storage

Dincer (2002, 2011) pointed out that the advantages of TES exceed the disadvantages. The benefits of utilising TES systems can be divided in three groups – benefits for the building owner, benefits for the environment and society, and benefits for the energy provider; summarised in Table 1.

Table 1: *Benefits of Thermal Energy Storage*

Groups	*Benefits of TES*
Benefits for the building owner	• Reduced heating/cooling costs, system's components size and initial costs • Improved indoor environmental quality • Less expensive electricity rates due to increased load factor for electricity
Benefits for the environment and society	• More viable utilisation of renewable energy resources (i.e., solar) • Energy distribution with low line losses and high generation efficiencies • Eliminating the need for additional power plants • Reduced source-energy consumption => fewer polluting emissions
Benefits for the energy provider	• Reduced peak electrical demand; increased efficiency of energy production • Increased utility's load factor

3 Criteria for design and evaluation of TES systems

The different TES concepts have different characteristics, possible applications, strengths and weaknesses. There are numerous criteria to evaluate TES systems and applications such as technical, environmental, economic, energetic, sizing, integration, and storage duration, Dincer (2011).

The first step of a TES project is to determine the energy load profile of the building. Parameters influencing the demand and load profile of the building are use of the building, internal loads, and the climatic conditions. Following steps are to determine the type and amount of storage appropriate for the particular application, the effect of storage on system performance, reliability and costs, and the storage systems or designs available.

It is useful to characterise the different types of TES depending on the storage duration. Short-term storage is used to address peak loads lasting from few hours to a day in order to reduce the sizing of the system and take advantage of energy-tariff daily structures. Long-term storage is used when waste heat or seasonal energy loads can be transferred with a delay of a few weeks to several months.

Related to the amount of storage required, a need exists for improved TES-sizing techniques. Realised projects reveal both undersized and oversized systems. Undersizing can result in poor levels of indoor comfort, while oversizing results in higher initial costs and waste of electricity or other primary energy sources if more energy is stored than is required.

The effect of TES on the overall energy system performance should be evaluated in details. The potential for more effective use of thermal energy equipment and the storage integration with the building energy supply system has to be investigated.

The economic justification for storage systems requires that the annualized capital and operating costs for TES be less than those required for primary generating equipment supplying the same service loads and periods.

4 Building TES systems and applications

A variety of TES techniques for space heating/cooling and domestic hot water have developed over the past decades, including Underground TES, building thermal mass, Phase Change Materials, and energy storage tanks. In this section, a review of the different concepts is presented.

4.1 Underground TES concepts

Seasonal thermal energy storage requires large inexpensive storage volumes and the most promising technologies were found underground. Underground Thermal Energy Storage (UTES) has been used to store large quantities of thermal energy to supply space cooling/heating, and ventilation air preheating. Energy sources include winter ambient air, heat-pump reject water, solar energy, process heat, etc. The most common UTES technologies are aquifer storage (ATES) and borehole storage (BTES) (Nordell, 2000). It is not possible, for geological or geo-hydrological reasons, to construct these systems at any location. Borehole systems are the most generally applicable ones.

The use of seasonal thermal energy storage can substantially reduce the cost of providing solar energy systems that can supply 100% of buildings energy needs. Utilising the ground as a seasonal storage of solar energy has been used in a number of countries in conjunction with district heating systems, Figure 1.

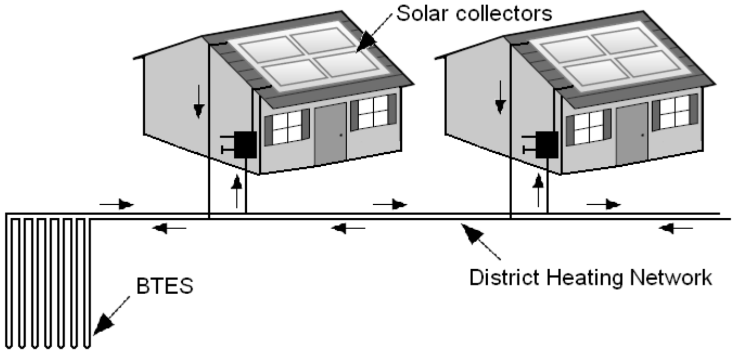

Figure 1. Seasonal storage of solar energy

The solar system in Anneberg (Nordell et al, 2000 and Lundh et al, 2008), is a good example of how solar heat is stored during summer and used for heating of family houses during winter, through low temperature floor heating systems.

In a demonstration plant in Neckarsulm (Schmidt et al, 2005), a residential and commercial area is connected to a central solar heating plant with seasonal storage. During the last years of operation solar fraction of 39% has been monitored. According to simulations the ground heat store will have an efficiency of about 65%, when a quasi-steady-state of operation of the storage media is reached.

In seasonal BTES of solar energy, high temperatures usually result in the storage at the end of the summer period. Such high temperatures have two drawbacks. First, the return temperature to the solar collectors is high which leads to low solar collector efficiencies. Second, heat losses from the storage are high: ~ 60% of the injected heat (Sibbit et al., 2007). In Chapius et al. (2009) is proposed a new strategy to overcome these drawbacks, by keeping the storage at a lower temperature.

Although different studies have shown potential for “free” high/low temperature BTES systems for space heating/cooling, the focus of innovative systems lies in the concept of Ground Source Heat Pumps with BHEs for combined heating and cooling applications, Figure 2. In this case heat pump is employed to decrease or increase the storage temperature for cooling or heating (Nordell et al., 1998).

Ground source heat pump systems (GSHP) have found broad application worldwide (Rybach et al., 2000 and Lund et al. 2004). The GSHP technology can offer higher energy efficiency for air-conditioning compared to conventional systems.

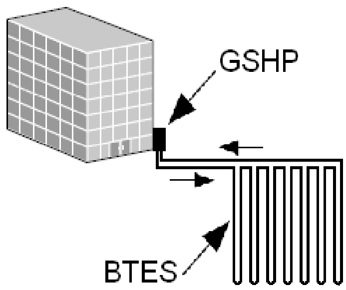

Figure 2. GSHP with BHEs

Desmedt et al. (2008) provided an overview of the results from a feasibility study to implementation phase of vertical BHEs in combination with GSHPs for a Belgian office building. The results show that primary energy savings can be obtained compared to conventional technologies. The ground storage system supplementary investment is paid back in 8 years.

A large scale BTES system for heating and cooling of Ontario Institute of Technology is presented in Dincer (2011). Monitoring results show annual energy savings for heating and cooling of 40% and 16% respectively. A payback period of 7.5 years is expected.

For UTES systems one of the most important factors is the required temperature level for the heating/cooling case involved. UTES systems are more efficient if the temperature requirement for space heating is low and for cooling is high. Using low-temperature heating/ high-temperature cooling systems will result in high COP for the whole system. Thermo-active building systems (TABS) for commercial buildings and floor heating systems for residential buildings have proven successful in practice.

In Fellin et al. (2003) simulation analysis of an office building, equipped with TABS is presented. Two different climatic zones and two possibilities of plant (traditional and an innovative, based on a GSHP) have been studied. The results show that TABS could ensure good comfort conditions in office buildings with heating loads in the range of 10 – 30 W/m² and moderate cooling loads, in the range of 30 – 60 W/m². By using a ground coupled heat pump, more than 40% of energy may be saved compared to the use of conventional system.

4.2 Building Thermal Mass Activation

Thermal mass is defined as the mass of the building that can be used to store thermal energy for heating/cooling purposes. In general the application has been found to be particularly suitable for climates with big diurnal temperature variations. The brief overview of concepts for activation of thermal mass for enhancing the energy efficiency of buildings presented here is focusing on Passive Thermal Mass Systems and Thermo-Active Building Systems (TABS).

In a simulation study evaluating the cooling energy of high rise residential buildings in Hong Kong (Bojic et al., 2005), results indicate that if the walls' thermal capacity is reduced, it would lead to a 60% increase of the cooling energy demand.

Givoni (1998) investigation shows the effectiveness of passive thermal mass and night ventilation in lowering the indoor air temperature during daytime for building with high thermal mass.

Cooling by night-time ventilation can be used if night temperatures are low enough to release heat from the building's thermal mass. For Europe the climatic potential for passive cooling of buildings by night-time ventilation has been analyzed in Artmann et al. (2007). It was shown that in Northern Europe there is significant potential for cooling by night-time ventilation. In Central, Eastern and Southern Europe passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. In such cases, Thermo-active building systems are considerably more effective.

TABS systems are used in multi-storey office buildings with a low heating load in winter (10-30 W/m^2) and a moderate cooling load in summer (30-60 W/m^2). With TABS the large thermal capacity of the building structure is used as energy storage and is thereby integrated in the overall energy strategy of the building. By utilising TABS, peaks in energy demand are flattened, and heat and cold can be transferred with time shift and at power levels which may differ from the actual demand.

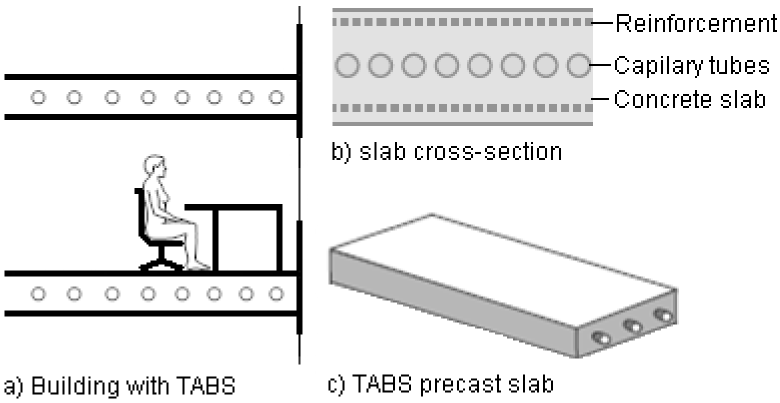

Figure 3. Thermo-active building systems (TABS)

Moreover, the large areas of the thermo-active surfaces allow for substantial heat flows between room and structure, even at relatively low temperature differences. For these reasons TABS are suitable for the application of low temperature heating and high temperature cooling sources, such as geothermal energy, groundwater or outside air (Koschenz et al., 1999 and Lehmann et al., 2007).

A comprehensive analysis of primary energy consumption of TABS is given by Henze et al. (2008), by a simulation study comparing the primary energy and comfort performance of ventilation assisted TABS system relative to a conventional VAV system. TABS heating is accomplished using a geothermal heat pump and TABS cooling using a geothermal heat exchanger. A primary energy savings of 20% were observed for the case with TABS.

A study by Rijksen et al. (2010) presents general guidelines for the required cooling capacity of an entire office building using TABS. Reductions up to 50% of the cooling capacity for a chiller can be achieved using TABS.

Results of Lehman et al. (2011) study, in Central European office building, show that the energy efficiency of TABS is significantly influenced by the hydronic circuit topology used. With separate zone return pipes energy savings of approximately 20–30% of heating as well as cooling demand, can be achieved, compared to common zone return pipes.

4.3 Phase Change Materials

The investigation of Phase Change Materials (PCM) for heating and cooling applications in buildings has a long history. Mehling et al. (2008) presents different concepts and potential applications of PCM for heating and cooling in buildings.

The applications of PCM can be divided into temperature control and storage of heat or cold with high storage density. The potential for temperature control are related to the potential for increasing the building heat storage capacity or thermal mass. In such applications, the focus is on the temperature regulation and the PCMs used should have phase change temperatures within the comfortable temperature range. In applications for the storage of heat or cold with high storage density, the focus is on the amount of heat supplied. In heating/cooling systems storage can be used to optimise the performance of the system in case of fluctuating demand or supply for heat or cold. The main advantage is the high storage density in small temperature intervals. In these applications, the PCM phase change temperature is significantly different from the comfortable temperature range.

The potential of using PCM in building materials to reduce temperature fluctuations is quite large, especially in lightweight buildings. Microencapsulated PCM incorporated into gypsum plasterboards or plasters has been developed commercially by different companies (e.g., microencapsulated paraffin with melting temperature in the range 23-26°C).

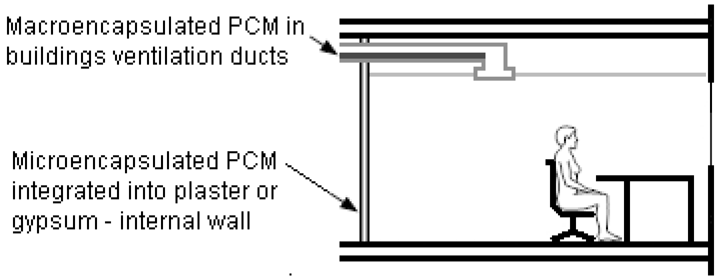

Figure 5. Examples of PCMs integrated in buildings

Another option is to integrate microencapsulated PCM into concrete. In an experimental study (Cabeza et al., 2007), of two concrete buildings, one of which includes 5% microencapsulated PCM in some walls, a temperature reduction of up to 4°C was achieved with the use of PCM. The results show the importance of night cooling to achieve this full-cycle every day.

It is important to check if the heat is not only stored, but also if it can be discharged on a daily cycle. In Neeper (2000) is presented a study on the thermal dynamics of a PCM wallboard under daily temperature variations. The results show that the daily storage capacity is limited to 300-400 kJ/m^2.

PCM can be integrated also in building systems. This approach can benefit from the fact that the PCM can be integrated in a way that the active ventilation leads to a better heat transfer coefficient at the surface of the PCM.

All examples till now have used air as heat transfer fluid and cold night air as a cold source. Using a liquid as a heat transfer fluid for heat rejection allows the use of more reliable natural cold sources like ground water, or artificial cold sources like compression or absorption chillers. On the demand side, water based storage systems for room air conditioning like TABS are already known. For these types of systems, use of PCM is also possible.

Cold storage is very common in conventional air-conditioning and industrial refrigeration systems. Because of its availability, high storage density, and low cost, water-ice is still by far the most widely used PCM. However, systems using other PCM than water-ice, with melting temperatures up to 20°C (8.3°C are most common ones) have also found broad application.

Seasonal cold storage by PCM (snow or ice storage) comprises two sources: natural ice and snow from precipitation, or snow or ice produced artificially using natural cold like cold air. In both cases the energy for cooling is practically free. Examples of both concepts are the Sundsvall Hospital Snow Cooling Plant in Sweden, and the Canadian Ice box/Fabrikaglace concept (Nordell et al., 2007).

The experience from the last decade shows that PCM applications for space cooling have found wider application however there are potential applications for space heating as well.

Solar air heating can be combined with the supply of fresh air in an energy efficient manner. A problem using air as heat transfer medium is that air stores too little heat due to its low heat capacity. The use of PCM seems promising because of the high heat storage density and because the PCM can have a regulating effect on the supply air temperature.

4.4 Energy Storage Tanks

TES tanks for use in heating, cooling, and domestic hot water applications have received increasing attention in recent years. The TES tank system most commonly employed at present is sensible, utilizing water as the storage medium. An effective system of that type should be stratified; it should hold separate volumes of water at different temperatures, with minimum mixing between them even during charging and discharging periods. TES tanks using latent storage have also found application. Typical systems employ the use of water-ice, ice-slurry, PCM, and PCM-slurries.

Large TES tanks for seasonal storage, as well as small tanks for diurnal or buffer storage are used in practice. The storage can be designed for peak shaving, for part- or full-load capacity.

TES tanks for seasonal storage can be designed to retain heat deposited during summer months for use during winter. The heat is typically captured using solar collectors. The tanks are sized to meet part or all of the heating and hot water requirements whether it is residential or commercial building.

Improving the thermal stratification of the stored water in solar energy systems is important since it can significantly improve the collector and system efficiency. Lavan et al., (1977) shows that even at very large flow rates, thermal stratification in hot water storage system can be maintained in cylindrical tanks.

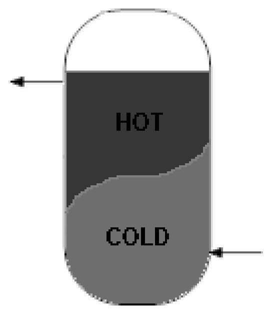

Figure 5. Thermally stratified hot-water storage tank

In Novo et al. (2010) a review on seasonal heat storage tanks and comparison with other ground storage possibilities is presented, focusing on their application in central solar heating systems.

A multi-tank liquid-water system for storing low-temperature solar-derived heat is investigated experimentally and analytically by Mather et al. (2002). The main advantages over single tank systems are foreseen to be a reduced installation cost plus reduced engineering costs.

Except for heat storage, TES tanks for cold storage are very common in conventional air-conditioning applications. Different storage includes water, water-ice, ice-slurry, PCM, PCM-slurries.

Analyses of the stratification decay in vertical cylindrical cool storage systems presented by Nelson et al. (1999) show that the degree of thermal stratification depends upon the length to diameter ratio, wall thickness to length ratio, the thermo-physical properties of the material of the storage tank, the type and thickness of the insulation, and the design of the water admission system.

5 Sustainable Buildings and Thermal Energy Storage

Thermal energy storage is advanced energy technology and there has been increasing interest in using it for thermal applications such as domestic hot water and space heating/cooling. TES has often been applied in standard buildings with the objective to demonstrate that the energy storage techniques could be successfully applied rather than to optimize the building performance. Indeed the design of the building and the design of the energy storage were often not coordinated and energy storage simply supplied the building demand whatever it might be.

Sustainable buildings need to take advantage of renewable and waste energy to approach ultra-low energy and zero emission buildings. Such buildings will need to apply thermal energy storage techniques customized for smaller loads and community based thermal sources. Lower exergy heating and cooling sources will be more common. Utilization of low-exergy heating and cooling sources requires that energy storage is intimately integrated into sustainable building design.

A coordinated set of actions for improved TES design and sizing is needed if the potential benefits are to be fully realized. Well designed TES systems can reduce initial and maintenance costs and can significantly reduce energy use and demand. Increased flexibility of operation, improved indoor environmental quality, conservation of fossil fuels and reduced pollutant emissions are other benefits.

At present IEA ECES Annex 23 “Applying Energy Storage in Buildings of the Future” is dealing with applying of energy storage in ultra-low energy buildings.

6 Conclusions

The present literature review study identifies the characteristics, possible applications, strengths and weaknesses of the different TES concepts. It aims at investigating and providing the basis for the development of new intelligent TES possibilities in buildings.

The study presents the use of TES in buildings for space heating/cooling and domestic hot water. TES concepts, including Underground Thermal Energy Storage, Building Thermal Mass, Phase Change Materials, and Energy Storage Tanks are described. The different energy storage concepts have very different characteristics, possible applications, strengths and weaknesses. Insight is given in the utilisation of solar energy and cold TES.

The selection of TES system mainly depends on the storage period required, economic viability, operating conditions, and so on. Specific parameters that influence the viability of a TES include facility thermal loads, thermal load profiles, availability of waste or excess thermal energy, electrical costs and rate structures, type of thermal generating equipment, and building type and occupancy. The economic justification for TES systems usually requires that annual capital and operating costs are less than the cost for conventional systems and equipment supplying the same service loads and periods. Well designed systems can reduce initial and maintenance costs and energy use and demand, and improve indoor environmental quality. A coordinated set of actions for improved TES design is needed if the potential benefits are to be fully realized.

Although the different energy storage solutions have found many applications in practice, it is still not clear how these can best be integrated into ultra-low energy and zero-emission buildings, capable of being replicated in a variety of climates and technical capabilities. Detailed studies on the dynamic performance and control strategies of the energy storage systems for different building types, weather conditions and user behaviour should be performed. Advanced design strategies for building and on-site integrated thermal energy storage solutions should be developed.

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