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Thermal Energy Storage and Energy Savings

5.1 Introduction

Thermal energy storage (TES) is a key component of many successful thermal systems. TES should allow for the minimum reasonable thermal energy losses and the corresponding energy savings, while permitting the highest appropriate extraction efficiency of the stored thermal energy. This chapter deals with the methods for describing and assessing TES systems, and practical energy-saving applications provided by using TES systems. The design and selection criteria for TES systems are examined. Further, energy-saving techniques and applications are discussed and highlighted with illustrative examples.

TES is considered by many to be an *advanced energy technology*, and there has been increasing interest in using this essential technology for thermal applications such as hot water, space heating, cooling, air-conditioning, and so on. TES systems have enormous potential for permitting more effective use of thermal energy equipment and for facilitating large-scale energy substitutions. The resulting benefits of such actions are especially significant from an economic perspective. In general, a coordinated set of actions has to be taken in several sectors of an energy system for the maximum potential benefits of TES to be realized. TES appears to be the best means of correcting the mismatch that often occurs between the supply and demand of thermal energy. More broadly, TES can contribute significantly to meeting society's needs for more efficient, environmentally benign energy use. The two main types of TES systems, sensible (e.g., water and rock) and latent (e.g., water/ice and salt hydrates), offer economic and other advantages, depending on the application. The selection of a TES system mainly depends on the storage period required, that is diurnal or seasonal, and such other factors as economic viability, operating conditions, and so on. In practice, many research and development activities have concentrated and continue to concentrate on efficient energy use and energy savings, leading to a broad array of energy conservation measures. In this regard, TES appears to have a major role to play as it is an attractive thermal technology.

TES generally involves the temporary storage of high- or low-temperature thermal energy for later use. Examples of TES applications include the storage of solar energy during the day for overnight heating, of summer heat for winter use, of winter ice for space cooling in summer, and of heat or cool generated electrically during off-peak hours for use during subsequent peak demand hours. Solar energy, unlike energy from fossil fuels, is not available at all times. Even cooling loads, which nearly coincide with maximum levels of solar radiation, are often present after sunset. TES provides an important mechanism to offset the mismatch between thermal energy availability and demand in this application.

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TES can also aid in the efficient use and provision of thermal energy in other situations where there is a mismatch between energy generation and use. Various TES processes have been investigated and developed for building heating and cooling, industrial energy-efficiency improvement, and utility power systems. The period of storage is clearly an important factor. Diurnal storage systems have certain advantages: capital investment and energy losses are usually low, units are smaller and can easily be manufactured off-site, and the sizing of daily storage for each application is not nearly as critical as it is for larger annual storage systems. Annual storage systems are likely to be economical only in multi-dwelling or industrial park designs. Such systems often require expensive energy distribution networks and novel institutional arrangements related to ownership and financing. In solar TES applications, the optimum energy storage duration is usually the one that offers the final delivered thermal energy at minimum cost, when integrated with the collection system and backup in the final application.

The economic justification for TES systems usually requires that the annualized capital and operating costs be less than the annualized costs of primary generating equipment supplying the same service loads and periods. TES is usually installed for two major reasons: (i) to lower initial costs and (ii) to lower operating costs. Lower initial costs are usually possible when the thermal load is of short duration and there is a long time gap before the load returns, because a small storage is adequate in such instances. Secondary capital costs may also be lower for systems incorporating TES. For example, the electrical service capacity can sometimes be reduced because energy demand is lower.

In order to perform a comprehensive economic analysis of TES, the initial costs must be determined. Equipment costs can be obtained from relevant manufacturers, and estimates of installation costs can be made. The cost savings and the net capital costs can be analyzed using the life-cycle cost method, or other applicable methods, to determine which system is most suitable for a given application.

Other items to be considered in TES economic analyses are space requirements and system reliability, and the interface to the delivery system for the application. An optimal energy storage application achieves a balance between maximizing the savings accrued in utility charges and minimizing the initial cost of the installation needed to achieve the savings. Consequently, the decision to install a storage system must be based on anticipated system loads, load characteristics, and generating capacity mix for an extended period. Uncertainty about the future economic outlook, life-style changes, and the availability of low-cost energy charging the storage system may lead to differing investment decisions if alternative technical solutions are feasible. These uncertainties may vary temporally and spatially. The technical characteristics of alternative technologies for situations in which TES systems are potentially attractive may also affect decisions.

In this chapter, TES systems and their applications are examined from an energy savings perspective, and possible energy-saving technologies are discussed in detail and highlighted with illustrative case studies of actual systems.

5.2 TES and Energy Savings

TES systems are an important element of many energy-saving programs in a variety of sectors, residential, commercial, industrial, and utility, as well as in the transportation sector.

TES can be employed to reduce energy consumption or to transfer an energy load from one period to another. The consumption reduction can be achieved by storing excess thermal energy that would normally be released as waste, such as heat produced by equipment and appliances, by lighting, and even by occupants. Energy-load transfer can be achieved by storing energy at a given time for later use, and can be applied to TES for either heating or cooling capacity.

The main objective of most TES systems, which is often to alter energy-use patterns so that financial savings occur, can be achieved in several ways (Dincer *et al.*, 1997a):

- The consumption of purchased energy can be reduced by storing waste or surplus thermal energy available at certain times for use at other times. For example, solar energy can be stored during the day for heating at night.
- The demand of purchased electrical energy can be reduced by storing electrically produced thermal energy during off-peak periods to meet the thermal loads that occur during high-demand periods. There has been an increasing interest in the reduction of peak demand or transfer of energy loads from high- to low-consumption periods. For example, an electric chiller can be used to charge a chilled water storage system at night to reduce the electrical demand peaks usually experienced during the day.
- The use of TES can defer the need to purchase additional equipment for heating, cooling, or air-conditioning applications and reduce equipment sizing in new facilities. The relevant equipment is operated when thermal loads are low to charge the TES, and energy is withdrawn from storage to help meet the thermal loads that exceed equipment capacity.

Each of these points is discussed separately in the following three subsections

5.2.1 Utilization of Waste or Surplus Energy

If a TES system is installed and charged using waste heat otherwise released to the environment, and if the energy is held and later used in place of added primary energy, overall energy consumption is reduced. To be economically feasible, the cost of the replaced primary energy should exceed the capitalization, maintenance, and operating costs of the TES system. The stored energy can in a sense be considered free, since it would otherwise be lost.

Useful waste or surplus thermal energy is available from many sources. Some examples are (i) hot or cold water drained to a sewer, (ii) hot flue gases, (iii) exhaust air streams, (iv) hot or cold gases or waste gases, (v) heat collected from solar panels, (vi) ground source thermal energy, (vii) heat rejected from the condenser of refrigeration and air-conditioning equipment, and (viii) the cooling effect from the evaporator of a heat pump.

Many of the TES applications in this category are designed for load leveling rather than waste energy recovery. The thermal energy stored is then in a higher grade rather than waste condition, being drawn from the conversion equipment during periods of low end-use demand for thermal energy. Such TES systems do not reduce energy use, and may actually cause it to increase because of TES inefficiencies. For example, the overall energy consumption for a task supplied using a storage, having an overall energy efficiency of 75%, will be one-third (i.e., $1/0.75 - 1$) greater than the energy consumption using a direct primary energy supply. The objectives of such systems are clearly not to reduce energy consumption, but rather to either reduce costs or allow the displacement of scarce fuels by more abundant fuels in an energy process.

Tomlinson and Kannberg (1990) point out that industrial production uses about one-third of the total energy consumed in the United States, much of it as hydrocarbon fuels. Therefore, energy-efficiency improvements in the industrial sector can have a substantial impact on national energy consumption levels. TES represents an important option for improving industrial energy efficiency. By storing and then using thermal energy that would otherwise be discharged in flue gases to the environment, less purchased fuel is used, plant thermal emissions are reduced, and product costs associated with fuel use are decreased. The following six industries, which account for approximately 80% of total US industrial energy use, have the highest potential for energy savings through implementation of TES: aluminum, brick and ceramic, cement, food processing, iron and steel, and paper and pulp. Most existing TES systems in an industry are found in iron and steel plants where they are used as regenerators to preheat air to about 600 °C. Opportunities exist for the reclamation of waste heat from stack gases in other industries as well. Estimates have shown that TES can result in potential energy savings in US industries of as much as 3 EJ per year.

In general, TES can reduce the time or rate mismatch between energy supply and energy demand, thereby playing a vital role in improved energy management. TES use can lead to savings of premium fuels and make a system more cost effective by reducing waste energy. TES can improve the performance of thermal systems by smoothing loads and increasing reliability. Therefore, TES systems are becoming increasingly important in many utility systems.

5.2.2 Reduction of Demand Charges

A major application of TES is to lower electrical demand and thus reduce electrical demand charges. Reduction in demand charges is accomplished by eliminating or limiting electrical input to electrically operated heating or cooling devices during the peak electrical demand periods for a facility. The devices are operated before the peak occurs (e.g., overnight) to charge TES systems. During the peak demand period, the heating or cooling equipment does not operate or operates at reduced levels, and the thermal loads are met with the heating or cooling capacity of the storage.

The electrical source that powers the heating or cooling equipment can be shut off, or have power limiters installed, to reduce electrical demand during the peak periods. A number of devices can be energized and de-energized in accordance with TES operating strategies. Some examples are equipment for building heating, cooling and air-conditioning, domestic water heating, process heating and cooling, refrigeration, snow melting, drying, ice-making, and so on.

The fundamental purpose of cool storage is to provide a buffer between the chiller and the building cooling load, thereby decoupling the chiller capacity and operating schedule from the building load profile, leading to energy consumption and demand savings and economic benefits through electrical load management. This application of TES can be beneficial in several ways, regardless of the chiller energy source. In many practical applications, the intention is to maximize the utilization of efficient base load generating plants and avoid the need for additional capacity. The benefits often justify offering rate structures that favor load shifting and peak shaving, and sometimes, financial incentives to reduce the cost of storage.

Figure 5.1 provides an example of daily load profiles for a building, with and without cool storage. Figure 5.1(a) represents the case with no storage, and Figure 5.1(b) shows a full-storage case. In the latter case, the TES provides enough storage capacity to meet the peak (i.e., 9:00 a.m. to 9:00 p.m.) cooling load, shifting the entire electrical demand for cooling to off-peak hours when there is little cooling load. This particular application achieves maximal benefits

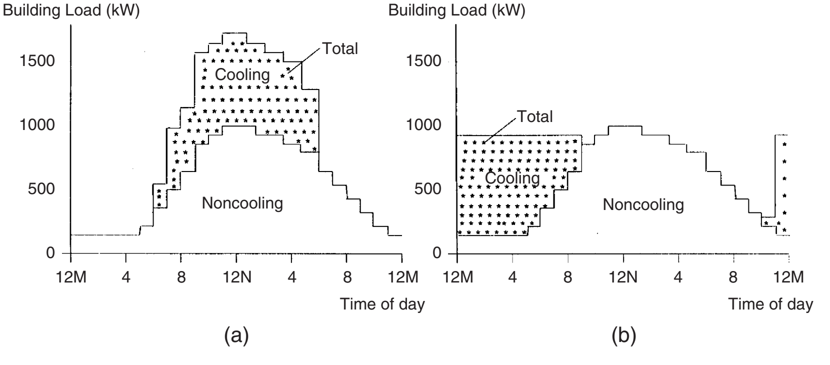

Figure 5.1 Daily load profiles of a building energy load: (a) no storage and (b) full storage (Dincer *et al*., 1997b)

in terms of demand charge reduction and use of favorable off-peak rates, both of which lower operating costs.

5.2.3 Deferring Equipment Purchases

The capacity of heating and cooling equipment is normally selected to match the part of the design-day load when the requirements for heating and cooling are close to maximum. These peak design loads occur for only short periods of time, resulting in excess capacity on average days. TES systems take advantage of the difference between the peak and average thermal loads to provide an opportunity to defer equipment purchases in a retrofit application, or reduce the equipment size in a new installation.

For example, consider a building with an average cooling load of 500 kW and a peak cooling load of 650 kW. The capacity of the existing chiller is 750 kW. A proposed expansion will increase the average cooling load to 700 kW and the peak to 850 kW. The new average load could be satisfied with the existing equipment, but the peak load could not be satisfied. An additional chiller with a capacity of 100 kW is required, based on the conventional method. As an alternative to providing a new chiller, a TES system could be incorporated to satisfy the peak cooling load. During off-peak hours, when the thermal load is less than the capacity of the existing chiller, the chiller would operate to maintain the desired building or process conditions, and excess capacity would be used to charge a chilled-water TES system (or other cool TES). When the cooling load exceeds the chiller capacity, chilled water would be drawn from storage. The benefits of the TES option can include capital savings and reduced operating costs. The reduced operating costs result from limiting the peak electrical load (and corresponding demand charge) to that required to provide only 750 kW of cooling instead of 850 kW, and from having less chilling equipment to maintain. Note that in either case the annual electrical consumption for cooling increases roughly in proportion to the new cooling loads (Anon, 1985).

The technique illustrated in the above example can also be used in new facilities. Then, TES permits the capacity of the thermal equipment to be selected closer to the average rather than the peak condition.

5.3 Additional Energy Savings Considerations for TES

The complete assessment of a TES application in a given facility requires an appreciation of several other criteria: energy requirements for heating, refrigeration and heat pump equipment, storage size limitations, thermal load profiles, and optimization of conventional systems (Anon., 1985; Dincer *et al*., 1997b). These topics are discussed in the following subsections.

5.3.1 Energy for Heating, Refrigeration, and Heat Pump Equipment

Electricity can be converted to thermal energy by electric resistance elements or by mechanical means. In resistance heating systems, each unit of electricity (1 kWh) is converted to heat (1 kWh), and the conversion efficiency is at or very near to 100%. Typical examples are electric baseboard heaters, electric water heaters, and slab heating systems.

Where refrigeration and/or heat pump systems are used to produce heating and/or cooling, the conversion efficiency, which is referred to as a *coefficient of performance* (COP), is normally greater than 100%. Heat pump systems require a heat source, which can be the outdoor environment or a waste heat stream. In many typical systems, the COP is approximately 3.5, where each unit of electrical input (e.g., 1 kWh) to the equipment produces about 3.5 kWh of heating or cooling. For example, a refrigeration system with a COP of 3.5 producing cooling at a rate of 350 kW has an electric power requirement of 100 kW (350 kWh/3.5). This behavior is important when TES systems, which aim at demand reduction, are being considered. When existing systems are being considered for conversion to TES arrangements, actual equipment COPs should be obtained from the manufacturers. Note that high-efficiency heat pump and refrigeration systems can have COP values in excess of 3.5.

Refrigeration system energy consumption per unit of cooling capacity increases as the evaporator temperature is reduced and as the condenser temperature increases. Producing ice at 0 °C, therefore, requires more energy than producing chilled water at 4 °C. Conversely, a heat pump requires more electrical power to produce hot water at 50 °C than at 35 °C. When the temperature variations are minor, the variations in electrical consumption can be approximated as negligible in many practical applications.

5.3.2 Storage Size Limitations

TES systems find application possibilities in a range of capacities, from only a few hours to seasonal storage. An example of seasonal storage is the collection of solar energy available during the summer for use in winter heating. Practical limitations such as space requirement and capital cost often restrict TES schemes to storage durations of a few hours to a few days.

As an example of these difficulties, consider a building or process requiring 1000 kW of chilling capacity for 900 h of full-load operation. For a TES, the annual cooling energy that must be stored (ignoring losses) is $900\,\text{h} \times 1000\,\text{kW} = 900{,}000\,\text{kWh}$. If ice is used as the storage medium, the quantity of ice required is 9,720,000 kg or 9720 m^3, since about 3 kg of ice is required to store 1 MJ of cooling capacity. Assuming a perfect tank with no standby heat losses and no oversize margin, a tank 2 m deep would cover an area the size of a football field. A water storage system would be at least 10 times larger. Costs for such large systems are unacceptable. For reasons illustrated in this example, greater attention has been paid in many instances to short term or diurnal TES systems, especially latent heat TES systems using phase change materials (PCMs).

5.3.3 Thermal Load Profiles

When thermal loads fluctuate, the potential exists for storing thermal energy to meet later energy requirements. Many buildings and units have load profiles conducive to TES.

Office buildings with low cooling requirements overnight and during the morning, and high cooling demands in the late afternoon, exhibit the optimum profile for TES. Often, the air-conditioning systems of these buildings are shut off at night. The combination of daytime part loads and night-time shutdown provides the daily equivalent of 15–20 h when a chilled water storage could be charged to meet the demand period.

Busy facilities, for example, hotels, hospitals, and industrial plants, are less likely candidates for full-storage systems as their load profiles are flatter. Less time is, therefore, available for charging the storage between the long cooling periods. However, these facilities are often suited to partial TES and peak shaving systems. For example, the base thermal load may be met by a chiller, and load peaks reduced using a combination of chiller and storage operation. In this case, the chiller contributes to the peak electrical demand, but by a lower amount than without TES.

The return on capital investment for a TES system can be maximized by careful sizing of the equipment. Often, compressor waste heat can be used for preheating domestic or process hot water. This by-product utilization can further improve the economics of a system.

Weather also affects the thermal load profile of a building, and is consequently a major factor in determining the feasibility of TES. Cooling storage is often advantageous in facilities where the summer weather profile includes a limited number of peak demand days and large temperature variations during a given 24-h period. Where TES for heating is considered, a minimum of 2200 degree days below 18 °C are usually required to make the project viable (Dincer *et al.*, 1997b).

5.3.4 Optimization of Conventional Systems

Existing heating and cooling systems should be upgraded where possible and properly maintained to reduce energy inefficiencies before implementing an active TES system. When reviewing conventional systems, the possibility of heat recovery from exhaust streams should be considered, for example, from boiler flue gases. The possibility of changing from batch to continuous industrial processes should also be examined so that direct heat recovery, without intermediate TES, can be used. This mode of operation often results in more effective heat recovery, no standby thermal losses, and reduced capital expenditure.

Control flexibility is an important tool for optimizing building TES systems, because exact operating modes and schedules vary continuously and are difficult to predict accurately. Systems designed either with manual control or with state-of-the-art computerized controls can be equally effective, provided system operation can be readily adjusted to meet actual site conditions.

Monitoring of TES system operation is required to track system performance and to identify operating problems and potential areas for future improvements. Small systems can be monitored with standard meters, gauges, and manual entry logs. Electronic instrumentation and control systems with automatic data logging, trend analysis, and other features are generally used in larger systems.

5.4 Energy Conservation with TES: Planning and Implementation

TES plays an important role in many energy conservation initiatives. In processes with large energy wastes, energy storage can result in a saving of fuels.

Energy may be stored in many ways, for example, mechanical and chemical energy storage. However, since in many economies, energy is produced and transferred as heat, the potential benefits of TES in energy conservation warrant detailed study. Thermal energy can be stored by cooling, heating, melting, solidifying, or vaporizing a material, the thermal energy becoming available when the process is reversed. Thermal storage by causing a rise or drop in material temperature is called *sensible heat storage*. Its effectiveness depends on the specific heat of the material and, if volume is important, the density of the storage material. Storage by phase change (solid to liquid or liquid to vapor) with no change in temperature is known as *latent heat storage*. Short-term storage is often used to manage peak power loads of a few hours to all day long in order to reduce the sizing of systems and/or to take advantage of the daily structure of energy tariffs. Long-term storage is possible when seasonal energy loads can be transferred over periods of weeks to several months, to cover seasonal needs. This type of storage is also called *seasonal storage*.

TES has a significant role to play in energy conservation efforts, and the following are the main steps in implementing an energy conservation strategy involving TES:

1. **Defining the main direct goals.** It is important to start by identifying clearly the goals of the project in a systematic way. This step should use an organized framework that facilitates deciding priorities and identifying the resources needed to achieve the goals.
2. **Identifying community goals.** Community priorities and issues involving energy use, energy conservation, the environment, and other local issues should be identified. Also, the institutional structures and barriers, and financial instruments should be identified.
3. **Scanning the environment.** The main objective in this step is to develop a clear picture of the community and to identify energy- and resource-related problems facing the community and its electrical and gas utilities, the existing organizational structures, and base data for evaluating the future progress of the program. Communication with local and international financial institutions,

project developers, and bilateral aid agencies can help capture new initiatives and explain lessons learned and viewpoints on problems and potential solutions.

4. **Increasing public awareness.** Governments can increase potential customers' awareness and acceptance of energy conservation programs by entering into performance contracts for government activities and publicizing the results. Also, international workshops to share experiences help to overcome the initial barrier of unfamiliarity in countries where TES applications have not been introduced.
5. **Building community support.** Obtaining the participation and support of local industries and public communities for an initiative requires understanding the nature of conflicts and barriers between given goals and local stakeholders, improving information flows, promoting education and advice activities, identifying institutional barriers, and involving a broad spectrum of citizen and government agencies.
6. **Analyzing information.** This step includes defining available options and comparing possible options in terms of factors, for example, program implementation costs, funding availability, utility capital deferral, potential for energy efficiency, compatibility with community goals, environmental benefits, and so on.
7. **Adopting policies and strategies.** High-priority projects need to be identified through approaches that are the best for the community. The decision process should evaluate options in terms of savings in energy costs, generation of businesses and tax revenues, and the number of jobs created, as well as their contribution to energy sustainability and other community and environmental goals.
8. **Developing the plan.** A specific plan of measures and activities should be developed. Once the draft plan has been adopted, it is important for the community to review it and comment on it. The public consultation process may vary, but a high level of approval should be sought.
9. **Implementing future programs.** This step involves deciding which future programs to concentrate on, with long-term aims being preferred over short-term aims. The options that have the greatest impact should be focused on, and all details defined. Potential financial resources need to be identified to implement the programs.
10. **Evaluating success.** The final stage involves evaluating and assessing how well the strategy performs, and helps detect its strengths and weaknesses and determine who is benefiting from it.

5.5 Some Limitations on Increased Efficiency

In terms of increased energy efficiency, there are a number of theoretical and practical limitations that apply to TES as well as to other processes.

5.5.1 Practical and Theoretical Limitations

The contributions that increased energy efficiency can make toward sustainable development are theoretically limited, because there exists a limit on the maximum efficiency attainable for any process. Such limitations are a consequence of the laws of thermodynamics (Moran, 1989). This concept, when applied to TES, implies that an ideal storage is one in which all of the input energy is restored after storage with no degradation of quality (i.e., temperature) and with complete recovery of energy used to drive the process (e.g., electricity to pumps).

In conventional engineering, the goal when selecting energy sources and utilization processes is not to achieve maximum efficiency. Rather, the goal is to achieve an optimal trade-off between efficiency and such factors as economics, sustainability, environmental impact, safety, and societal and political acceptability. Consideration of these factors leads to practical limitations on increased energy efficiency. For energy efficiency to have an increased contribution toward sustainable development, the position of the optimum among these factors will have to shift toward increased energy utilization efficiency (while recognizing the theoretical limitations on increased energy efficiency).

To assess the potential of increased energy efficiency as a measure for promoting sustainable development, the limits imposed by the existence of maximum theoretical energy efficiencies must be clearly understood. Lack of clarity on this issue has, in the past, often led to confusion and misunderstanding. Part of the reason for this problem is that conventional energy analysis often does not evaluate efficiencies as a measure of how nearly the performance of a process approaches the ideal, or maximum possible. The difficulties inherent in energy analysis are in part attributable to the fact that such an analysis methodology considers only energy quantities, and ignores energy quality and the fact that energy quality is continually degraded during processes. Here, higher quality energy forms are taken to be those that can be used for a wider range of tasks; for example, high-temperature steam is more useful than lower temperature steam as the hotter steam can satisfy all the heating uses of the lower temperature steam and more.

5.5.2 Efficiency Limitations and Exergy

One way to deal with energy forms of different qualities is to consider exergy. The exergy of a quantity of energy or a substance is a measure of its usefulness or quality, or a measure of its potential to cause change. Exergy analysis has recently been proposed by many scientists and engineers as a technique for thermodynamic assessment that overcomes most, if not all, of the problems associated with energy analysis (e.g., Moran, 1989; Rosen and Dincer, 1997a; 1997b). In practice, the authors feel that a thorough understanding of exergy and how exergy analysis can provide insights into the efficiency and performance of energy systems is required for the engineer or scientist working in the area of energy systems and the environment.

As environmental concerns such as pollution, ozone depletion, and global climate change became major issues in the 1980s, environmental concerns come to represent another factor related to efficiency limit. Consequently, interest developed in the link between energy utilization and the environment. Since then, there has been increasing attention to this linkage. Many scientists and engineers suggest that the impact of energy-resource utilization on the environment is best addressed by considering exergy. Exergy appears to be an effective measure of the potential of a substance to impact the environment. Although many studies exist concerning the close relationship between energy and the environment, there have been limited works on the link between exergy and environment concepts (Rosen and Dincer, 1996; 1997a).

Another use of exergy in TES work is in comparisons. TES systems have been investigated and applied for many years. These experiences have shown that although many technically and economically successful TES systems exist, no broadly valid basis for comparing the achieved performance of one storage with that of another operating under different conditions has found general acceptance. The development of such a basis for comparison has been receiving increasing attention, especially using exergy methods. Exergy analysis, which is identified as one of the most powerful ways of evaluating the thermal performance of TES systems, is based primarily on the second law of thermodynamics, as compared to energy analysis, which is based on the first law, and takes into account the quality of the energy transferred.

5.6 Energy Savings for Cold TES

In a TES for cooling capacity, “cold” is stored in a thermal storage mass. As shown in Figure 5.2, the storage can be incorporated in an air-conditioning or cooling system in a building. In most conventional cooling systems, there are two major components (Dincer and Rosen, 2001):

- a chiller – to cool a fluid such as water, and
- a distribution system – to transport the cold fluid from the chiller to where it cools air for the building occupants.

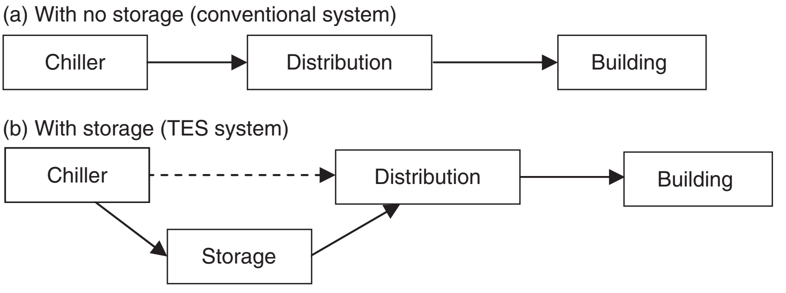

Figure 5.2 Representation of two cooling TES systems for buildings: (a) with no storage and (b) with storage

In conventional systems, the chiller operates only when the building occupants require cold air. In a cooling system incorporating TES, the chiller also operates at times other than when the cooling is needed.

During the past two decades, much TES technology, especially cold storage, has matured and is now accepted by many as a proven energy conservation technology. However, the predicted payback period of a potential cold storage installation is often not sufficiently attractive to give it priority over other energy-efficient technologies. This determination is often made, because full advantage is not made of the many potential benefits of cold storage, or because the cold storage sizing is not optimized. Some recommendations for optimizing the payback period of cold TES systems follow.

For new facilities, cold storage should be carefully integrated into the overall building and its energy systems so that full advantage is taken of the potential benefits of cold TES, including

- reduced pipe and pump sizes for chilled water distribution;
- reduced duct and fan sizes for low-temperature air distribution;
- reduced operating and maintenance costs;
- reduced electricity consumption and therefore energy costs; and
- increased flexibility of operation.

Smaller chiller and electrical systems lead to initial cost advantages. The sizing of the cold storage system should be optimized, as opposed to the typical process of considering full storage and one or two levels of partial storage versus a conventional system. A practical method to assist in determining the optimum system size should be developed. Also, the value should be accounted for of the gain in usable building space due to less space being required for mechanical system components when cold TES is used.

For existing facilities, potential advantages of cold TES that should be evaluated include

- modifying the existing chillers to make ice versus the purchase of a new machine;
- using spare chiller capacity by adding a cold TES system;
- using cold storage to increase cooling capacity in situations where chiller and electrical service capacity are fully utilized;
- sizing the cold storage system optimally as opposed to taking the best of only a few options; and
- using available low-temperature air and water to advantage through “free cooling,” where practical.

In summary, a cold TES system can benefit users in three ways:

- **Lower electricity rates.** With cold TES, chillers can operate at night to meet the daytime cooling needs, taking advantage of lower off-peak electricity consumption rates.

- **Lower demand charges.** Many commercial customers pay a monthly electrical demand charge based on the largest amount of electricity used during any 30-min period of the month. Cold TES reduces peak demands by shifting some of those demands to off-peak periods. Furthermore, some utilities provide a rebate for shifting electrical demand to nighttime or other off-peak periods.
- **Lower air-conditioning system and compressor costs.** Without cold TES, large compressors capable of meeting peak cooling demands are needed, whereas smaller and less expensive units are sufficient when cold TES is used. Also, since water from a cold TES may be colder than conventional chilled water, smaller pipes, pumps, and air handlers may be integrated into the building design to reduce costs further.

5.6.1 Economic Aspects of TES Systems for Cooling Capacity

TES-based systems are usually economically justifiable when the annualized capital and operating costs are less than those for primary generating equipment supplying the same service loads and periods. TES is mainly installed to lower initial costs of the other plant components and operating costs. Initial equipment costs are usually lower when intervals between periods of energy demand are large. Secondary capital costs may also be lower for TES-based systems. For example, the electrical service equipment size can sometimes be reduced when energy demand is lowered.

In complete economic analyses of systems including and not including TES, the initial equipment and installation costs must be determined, usually from manufacturers, or else they must be estimated. Operating cost savings and the net overall costs should be assessed using life-cycle costing or other suitable methods to determine which system is the most beneficial.

Utilizing TES can enhance the economic competitiveness of both energy suppliers and building owners. For example, one study for California indicates that, assuming 20% statewide market penetration of TES, the following financial benefits can be achieved in the state (CEC, 1996):

- For energy suppliers, TES leads to lower generating equipment costs (30 to 50% lower to serve air-conditioning loads), reduced financing requirements (US$1–2 billion), and improved customer retention.
- For building owners statewide, TES leads to lower energy costs (over one-half billion US dollars annually), increased property values (US$5 billion), increased financing capability (US$3–4 billion), and increased revenues.

5.6.2 Energy Savings by Cold TES

Cold TES has been shown to be able to reduce building cooling costs, which can be significant. Stored cooling capacity can be used either to meet the total air-conditioning load so that chillers remain off during the day, or to supplement the chiller so that it only has to satisfy part of the load.

Numerous cities throughout the world, including many in the United States, are faced with increasingly high energy costs. Often, these costs are in large part due to electrical demand charges in addition to energy consumption costs. Many electrical utilities experience difficulties in maintaining sufficient capacity to meet the peak customer demand while at the same time supplying reasonably priced electricity. One way to defer or avoid the construction of new power plants is to level local electrical loads over time. Such leveling can be achieved in part by shifting the electrical loads in buildings due to heating, ventilating, and air-conditioning equipment to periods of lower overall electrical usage. This load shifting can be accomplished by applying TES technologies, and utility companies and governments in many countries offer incentives to encourage such uses of TES.

Strong interest in TES systems for commercial buildings led the Air-Conditioning and Refrigeration Institute (ARI) in the United States to establish in May 1997 a new product section, Thermal Storage Equipment, to promote the attributes of TES and to develop a standard for rating the efficiency of TES equipment. Members of the product section have identified many TES case studies illustrating the technical impacts and financial benefits of TES use. The ARI is the national trade association representing manufacturers of more than 90% of United States, which produce central air-conditioning and commercial refrigeration equipment.

Energy-Saving Strategies for Cold TES

Three basic strategies are typically employed for reducing peak electricity use with TES, as shown in Figure 5.3: full, near-full, and partial storage. With full storage, the chiller and storage tank are sized so that the chiller does not run during the peak hours even on the hottest days, while with partial storage that equipment is downsized and the smaller chiller runs continuously on hot days. Thus full storage allows electricity costs to be lowered significantly, while partial storage reduces TES system capital costs. To achieve some of the benefits of both modes of operation, one can also utilize a near-full storage strategy, in which the chiller runs at a reduced level during peak hours.

With these strategies, five major types of TES system are usually utilized, as shown in Table 5.1. The first type, which uses chilled water as the storage medium, has the advantage of being compatible with existing chillers, and is usually more efficient than the other types. However, this TES type requires larger storage tanks than the other types, which use different storage media. The second type of TES, which uses a “eutectic salt” water solution as the storage medium, stores cooling capacity by freezing the storage solution at a temperature typically near 8.3 °C. The main advantages of this TES type are that (i) by storing cold through a phase change (freezing), tanks smaller than that used for chilled water are required, and (ii) by freezing at 8.3 °C, standard chillers producing 5 °C chilled water in commercial facilities can be used. The main disadvantage is that the tank typically cools the water for the distribution system to only 8.5–10 °C, which accomplishes less building dehumidification and requires more pumping energy.

The last three types in Table 5.1 have ice as the storage medium, and differ in how the “cold” from the ice is distributed throughout the building. Before the differences in the distribution systems are considered, the features of their common components (ice storage and chiller) are taken into consideration.

The main advantage of ice storage is compactness, which can be a significant benefit where space is a premium, as ice tanks often are 10 to 20% of the size of comparable chilled water tanks, and 30

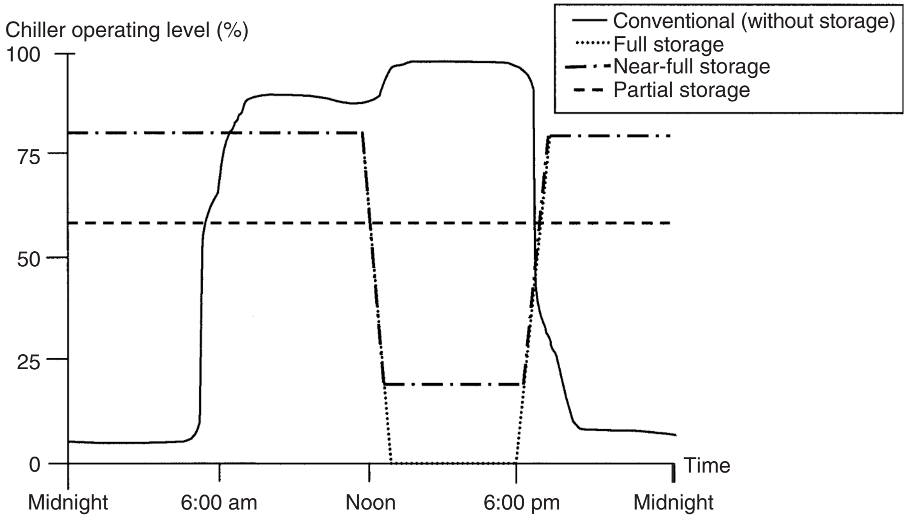

Figure 5.3 Comparison of conventional and cold TES systems for electricity use

Table 5.1 Major types of TES cooling systems

Chiller	Storage	Distribution
Conventional	Chilled water	Conventional water
Conventional	Eutectic salt/water solution	Conventional water
Ice-making	Ice	Conventional water
Ice-making	Ice	Cold air
Ice-making	Ice	Unitary (Rooftop) l

Source: CEC (1996).

to 50% of the size of eutectic salt tanks. Additional benefits of ice storage systems, when used with cold air or rooftop distribution systems, are increased dehumidification and fan energy savings. The major disadvantage of ice systems is that they are not compatible with most conventional chillers that use cold water, and so ice-making chillers must be used, which use more electricity than conventional water chillers because of the lower temperatures required to freeze water.

Although ice storage systems can be used with conventional chilled-water distribution systems, they are particularly beneficial when the distribution system (fans and ducts) is designed to take advantage of the lower temperatures available to produce cold air, and correspondingly downsized. The benefits of such downsizing include lower distribution-system initial costs, lower distribution-system energy use for fans and pumps (by 40% or more), and smaller duct passages, which can mean lower floor-to-floor heights in buildings, allowing architects to design additional floors without increasing building height, and lower net costs per unit area of floor space.

The first four TES types listed in Table 5.1 are used mostly with typical chilled-water distribution systems in larger buildings. The last type is used with unitary systems, including those used in typical single-family residences having an outdoor condensing unit and indoor coil as well as gas or electric heating, or having heat pumps and related air handlers. Unitary systems also include single-package systems that are roof mounted on low-rise commercial buildings and, in certain geographical locations, some residences. These unitary systems use a “direct-expansion” process in which the refrigerant, not chilled water, cools the air that is delivered directly to the structure. Unitary systems are typically small, air cooled, and not as efficient as most of the water-cooled chilled water systems used in larger buildings. Because of their lower efficiencies, air-cooled unitary systems may undergo significant improvement efforts in the near future.

Analysis of TES Savings

A major focus of this study is on determining the increase or decrease in energy use and demand due to TES. TES generally reduces the fuel or energy required and changes the time at which electricity is used. In order to quantify the source energy impact of TES and to calculate the source energy savings, the incremental energy method (or marginal plant method) can be used (CEC, 1996). The incremental energy method is consistent with evaluation methods for several TES programs. In this method, decisions about which resource to use are based on how the costs of providing power change for a marginal or incremental change in electricity use from current levels. Many believe that marginal costs should be used in the design of electric rates so that they lead energy users to utilize energy resources prudently.

Following these concepts, a standard practice methodology (SPM) is commonly used for evaluating the cost effectiveness of both new supply resources and demand-side management (DSM) measures (CEC, 1996). DSM measures include programs for energy efficiency (often aimed at reducing electrical energy use) and load management (primarily aimed at reducing electrical peak demand), and are often considered as a special type of supply-side resources in resource planning decisions. The SPM evaluates DSM programs by comparing electrical energy and demand savings to the marginal costs for providing those quantities. This methodology has gained international acceptance as a rational way to evaluate DSM programs – including TES. With the SPM approach, DSM program saving can be expressed as follows:

$$D = \sum_{i=1}^{n} [(\text{kWh savings})_i (\text{marginal cost of kWh})_i] + \sum_{i=1}^{n} (\text{kWh savings}) \tag{5.1}$$

where n denotes the number of time periods in the program. In other words, DSM program cost savings are evaluated by determining the energy consumption and demand savings in each of n time periods, multiplying each of those savings by the marginal costs for that time period, and then summing the cost savings over all time periods. Using the SPM, the year can be divided into n time periods, each with different marginal costs (for both kW and kWh). Note that utility companies often define the summer peak period as working weekdays from noon to 6:00 p.m., and that the winter peak period is much less dominant than the summer peak in determining new (marginal) capacity decisions.

The "marginal electrical energy cost" (in \$/kWh), referred to in Equation 5.1 as "the marginal cost of a kWh," for a time period equals the cost of fuel (in \$/kWh) multiplied by the average heat rate (or the incremental energy rate R). Thus, R can be expressed (in kWh fuel/kWh electricity):

$$R = \text{marginal electrical energy cost (\$/kWh)/marginal cost of plant's fuel (\$/kWh)} \tag{5.2}$$

Equation 5.2 can be substituted into the energy terms in Equation 5.1, after dividing all marginal energy cost terms in Equation 5.1 by the marginal fuel cost, to develop an expression for source energy savings:

$$DS = \sum_{i=1}^{n} [(\text{kWh savings})_i R_i] \tag{5.3}$$

When evaluating source energy savings with Equation 5.3 or other benefits of TES, care should be taken to account appropriately for the difference between utility source energy use (i.e., fuel used at the power plant to generate electricity), the electricity generated at the power plant, and the electrical energy provided to the user site. While transferring electricity over power lines from the power plant to the user, energy is lost because of resistance in the power lines (line losses). Line losses are often neglected even though they are sometimes significant (e.g., 10%). Of particular significance in TES assessments are the facts that line losses vary temporally, being greater when the lines are more fully loaded and when the ambient temperature is higher. Thus, line losses are often higher during summer peak hours, so TES can reduce energy use by shifting electricity use to times of lower line losses.

Assessments do not always account for line losses as utilities are concerned about marginal costs sometimes at the power plant (or generation) level, and at other times at the user site (or distribution) level. When evaluating the marginal energy cost M at the distribution level, the generation-level marginal costs are increased to reflect the line losses to the distribution level, as follows:

$$M(\text{\$/kWh at site}) = \text{MFP} \times R \times \text{LLF} \tag{5.4}$$

where MFP is the fuel marginal price at the power plant (in \$/kWh of fuel) and LLF is the line loss factor, evaluated as the ratio of kWh electric exiting the power plant to the kWh electric delivered to the site.

Finally, the TES-derived source energy savings T can be determined considering all assessment periods and accounting for line losses as

$$T = \sum_{i=1}^{n} [(\text{kWh electric savings})_i \times R_i \times \text{LLF}_i] \tag{5.5}$$

An alternate method that air-conditioning engineers can use to characterize this information involves evaluating the fractional source energy savings due to TES. This fraction can be calculated as

$$F_{\mathrm{TES}} = F_{\mathrm{ES}} \times F_{\mathrm{EST}} \tag{5.6}$$

where F_{TES} is fractional source energy savings due to TES for the annual cooling load, F_{ES} is fractional source energy savings per kWh electric shifted, and F_{EST} is the fraction of the annual kWh electric shifted by TES.

In Equation 5.6, the second term on the right-hand side varies with the TES system, typically ranging from about 0.40 for hospitals with partial storage systems to about 0.65 for office buildings with full-storage systems (CEC, 1996).

5.6.3 Case Studies for TES Energy Savings

Thousands of cold TES systems have been operating in the world, particularly in developed countries, for years in hospitals, public and private schools, universities, airports, government facilities and private office buildings, and in industrial process cooling applications. Described below are several case studies reported by the IEA-HPC (1994), OECD (1995), CEC (1996), ARI (1997), Mathaudhu (1999), and Dincer and Rosen (2001), which demonstrate how TES systems provide energy savings and reduce the environmental impact, and which illustrate some clever applications of TES equipment in new buildings to reduce initial costs. In this section, several examples are given to illustrate the energy savings achievable through TES.

TES Energy Conservation Project (California, USA)

This case study considers a project incorporating TES and other energy conservation features into systems for using electricity and water and into the design of the building envelope. The TES project was applied to a Center in California, USA. The Center's major areas include a central operations control center and computer room (which operate throughout the day), administrative and engineering offices, and clerical and conference rooms (all of which have 10 hours per day operation). To comply with California State energy efficiency standards, packaged rooftop heat pump units were selected for the base mechanical system. A 20-year life-cycle analysis was performed to review alternate mechanical systems using a variable-air-volume (VAV) system with electric reheat; with shut-off VAV boxes; and with fan-powered VAV boxes. This analysis determined that fan-powered VAV boxes with electric reheat using an air-cooled chiller were the most cost effective, with a 5.5-year payback period.

At the design stage, the client requested a study to consider incorporating a TES system. The selected system consisted of a fan-powered, variable-volume system with electric reheat, low-temperature supply air (6 °C), a chilled water plant, air handlers with variable speed drives, and ice storage tanks. This system resulted in 30% greater energy savings than mandated by the California State Energy Efficiency Standards and ANSI/ASHRAE/IESNA Standard 90.1.

Designing the HVAC system for the building (Figure 5.4) efficiently is considered a challenge because of the constant fluctuation in the number of people present (50 to 370). Some of the areas have 24-h occupancy, and many employees are dispatched to the field after coming to work in the morning and then meet at the end of the day for reporting.

In this application, seven thermal ice storage tanks, with a total capacity of 1330 ton-hours, provide 1095 ton-hours of full-load off-peak cooling. Other energy conservation measures used to increase efficiency include the following (Mathaudhu, 1999):

- Low-temperature air supply at 6 °C is used instead of conventional air supply at 13 °C to help reduce the supply fan size from 20,760 L/s to 14,745 L/s.

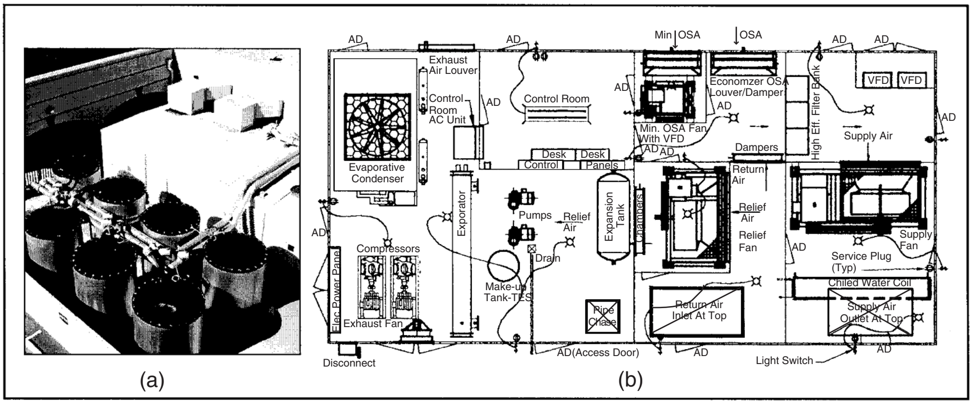

Figure 5.4 Custom-built unit and sensible ice storage tanks (a) and custom-built unit layout (b) (Reprinted from Mathaudhu (1999) by permission of ASHRAE)

- Variable speed drives are provided for supply, return/relief, and outside air fans. All air-handling unit fans and pumps have high-efficiency motors. The outside air fan speed is controlled by CO_2 sensors located in the main return-air duct.
- Fan-powered VAV boxes mix filtered plenum air with primary air supplied at 6 °C. Additional heating requirements are provided by three-stage electric heaters in VAV boxes. The secondary fan in the VAV box has a variable-speed controller to fine-tune the plenum air quantity for recirculation.
- A direct digital control energy management system helps optimize the system operation.
- A high-efficiency heat pump unit maintains comfort level after normal operating hours in the evenings, on weekends and holidays, and for the continuously occupied central control room.
- An evaporative condenser is used rather than a cooling tower to increase system efficiency.

Further, energy conservation features include R-19 wall insulation, R-30 roof insulation, low-emissivity glass windows, high-efficiency T-8 lamps, daylight sensors, occupancy light sensors, skylights, and low-water-consumption plumbing fixtures and metering faucets.

Locating the air-handling unit, chiller, pumps, and cooling tower became a challenge, because the architect had counted on the HVAC system being packaged rooftop heat pump units, and had not planned for the additional space. The installed cost for all of the central plant equipment with an architectural enclosure, but excluding the energy management controls, was over budget by at least $130,000. An alternate plan including a custom unit to house all the equipment was determined to be more cost effective. The unit would be factory-piped and wired with a complete energy management control system. The custom unit consists of a supply fan (plug type), a return/relief fan (plug type), minimum outside air fan (FC fan), prefilters and high-efficiency filters, two multiple-stage reciprocating compressors, evaporative condenser cooler, variable speed drives for supply, return/relief, and outside air fans, water/glycol circulating pumps, and a control room with complete direct digital control panels and a computer. The control room within the custom unit is designed to be accessible at all times so that clients can observe the system operation. This control room is cooled by a through-the-wall air conditioner that is factory-mounted on the common wall to the evaporative condenser area and the control room.

Although the application of packaged roof-mounted heat pumps would have been the least costly option for installation, the client preferred using a chiller system with a VAV system. Therefore, this system was used as the base case. For the TES system, the time-of-use load leveling strategy provided a payback period of 3.5 years. The time-of-use peak-hour shift option provided a payback period of 7.8 years, and the time-of-use mid- and peak-hour shift provided a payback period of 17.7 years, compared to the conventional base case of off-peak cooling. A 20-year life-cycle analysis was used to project these payback periods. The client chose to use the time-of-use peak-hour shift strategy. The supply air temperature of 6 °C helped reduce the sizes and related costs for the supply fan, return fan, air-distribution duct, duct insulation, fan motors, and variable frequency drives, resulting in about $56,000 savings per year. The custom air-handler/chiller system helped reduce mechanical central plant costs by about $150,000, to $550,000 from $700,000.

The seven thermal ice storage tanks (Figure 5.4) provide the flexibility to isolate a tank in case of any failure and still provide over 85% off-peak cooling. The system installed in the facility has demonstrated overall a high level of occupant comfort, while proving itself as an energy-efficient and cost-efficient choice. On the basis of data for building operation for almost 3 years (in the late 1990s), its performance was observed to be slightly better than projected. In other words, the study predicted annual electrical consumption of 623,400 kWh, while the actual value observed was 566,900 kWh.

California Energy Commission's TES Program (California, USA)

In this section, we consider the California Energy Commission's "Opportunity Technology Commercialization (OTCOM)" program to increase the market penetration of energy technologies such as TES that offer, among other factors, significant energy benefits. OTCOM's TES Systems Collaborative Program Commission requested an analysis of the source energy (power plant fuel) savings of electric TES systems in California and of other TES impacts. Besides environmental and economic development benefits, the study identified significant potential for energy savings. In many California TES installations, 40–80% of the annual electricity used for air-conditioning can be shifted from day to night, yielding source energy savings per kWh shifted ranging from 12–43%, depending on the estimation method employed. The results predicted that if TES achieves 20% market penetration by the year 2005, enough source energy would be saved from load shifting (ignoring energy impacts) to supply the energy needs of over a fifth of all new air-conditioning growth projected by the Commission during the next decade. When the site energy savings are combined with the TES source energy savings from shifting load noted above, TES can achieve even greater energy savings. Again, assuming 20% market penetration by 2005, TES was predicted to be able to, in total, save enough energy to supply over a third of the new air-conditioning load projected by the Commission. Of course, the source energy savings for a particular TES system in a particular building depend on a number of factors that are related to the system and its environment (CEC, 1996).

Anova Verzekering Co. Building (Amersfoort, The Netherlands)

This relatively recent TES provided energy savings and reductions in pollutant emissions (Table 5.2). In the application, a groundwater aquifer TES system was installed as part of a space-conditioning unit in a newly renovated office building of Anova Verzekering Co. An electric heat pump is used to supply hydronic heating and cooling. Accounting for the subsidy of US$212,000 received from the Dutch government, which is equivalent to 20% of the total initial system costs, the reduced energy costs due to TES are expected to lead to a payback period of 6.5 years for the additional investment costs due to TES. In the case study, primary energy consumption decreases because of TES by over 40%, even though electricity use increases.

City of Saarbrucken (Saarbrucken, Germany)

The city of Saarbrucken, Germany, implemented a strategy in the 1980s to reduce energy consumption through seasonal TES, district heating, and by increasing the use of renewable energy (e.g., solar thermal, solar photovoltaic energy, and small hydropower). Between 1980 and 1990, the city achieved significant energy use savings, including a 15% reduction in overall heating demand

Table 5.2 Annual energy savings and emission reductions for the case study[a]

Commodity	Conventional system	TES-based system	Reduction for TES-based system
Consumptions			
Natural gas (m^3)	215,800	95,500	120,300 (56%)
Electricity (kWh)	395,550	511,500	−84,000 (−21%)
Primary energy (m^3)[b]	322,000	179,000	143,000 (44%)

[a] Adapted from IEA-HPC (1994), where further details are available.
[b] Primary energy is calculated as the equivalent amount of natural gas on the basis of the assumption that 0.25 m^3 gas is used in the generation of 1 kWh of electricity.

and a 45% reduction in heating consumption for the municipal buildings. Some of the energy savings resulting from this successful energy program are attributable to TES (OECD, 1995).

Kraft General Foods Headquarters Building (Northfield, Illinois, USA)

All daytime air-conditioning loads are presently being met at this facility by melting ice that is made and stored overnight. It is anticipated that additional loads from future expansion will be met by operating some of the chillers during the day as well as at night. The building was designed to pump 2.2 °C water to the air-handling units, which in turn provide 7.2 °C air to the building. These temperatures, which are lower than that required for non-TES-based systems, permit the use of smaller pipes, pumps, air-handling units, and ductwork, resulting in lower initial capital costs for the system. Annual electric bills for this building are nearly US$200,000 lower than that for an almost identical building just three miles away, which does not use a TES system.

Chrysler Motors Technology Development Center (Auburn Hills, Michigan, USA)

Since opening in 1990, the Chrysler Motors Corporation's new technology development center has achieved both equipment and operating cost savings by using a 68,000 ton-hour chilled-water TES system. The TES capacity allowed the center's chiller plant to be downsized from 17,710 tons, which would have been needed to meet peak cooling loads, to 11,385 tons. Chilled water is stored in the TES system at night and supplements chiller operation during peak cooling conditions the following day. Reduced chiller costs more than offset the cost of the TES installation, resulting in initial savings of US$3.6 million. In addition, the TES system shifts over 5000 kW of peak electrical demand to off-peak periods, saving over US$1 million per year.

San Francisco Marriott Hotel (San Francisco, California, USA)

Using a TES system in tandem with a real-time pricing strategy from the local utility, this hotel is expected to save US$135,000 in annual cooling costs. Only 1800 ton-hours of ice storage are needed, enough to satisfy the 450 ton cooling load during the daily peak-rate time period, which lasts only 2 to 3 h under the real-time pricing schedule. Over one-third of the installed cost of the TES system will be covered by a rebate from the utility; the rest is expected to be recouped in less than two years of operation.

Texas A&M University (Corpus Christi, Texas, USA)

In August 1997, the Central Power & Light (CPL) Co. presented Texas A&M University-Corpus Christi with a US$431,800 incentive award for the university's participation in a TES program that is resulting in substantial energy savings. The university system uses the bulk of its electricity during off-peak evening hours, allowing CPL to shift some of its electric load from peak usage times and to share the annual cost savings of up to US$150,000 with the university. Texas A&M-Corpus Christi invested approximately US$900,000 to purchase and install the TES equipment, which became operational in January 1995, and was predicted to recover that cost through energy savings within five years. The US$431,800 incentive includes US$20,400 for installing high-efficiency equipment for cooling and heating the campus. The remaining incentive was provided through CPL's energy efficiency program, wherein the university was offered US$200 for every kW of electricity load shift from CPL's peak daytime load to off-peak evening hours. The university reduced electric peak demand by approximately 2057 kW, earning a US$411,400 incentive. CPL worked with the university to install an 11,800 ton-hour thermal storage system with a water storage capacity of 5300 m^3. The university also installed a 500-ton industrial heat pump for heating, which CPL estimated, would save the university approximately US$90,000 annually in energy costs. The heat pump captures waste heat from the university's 3000-ton chiller plant, and recirculates it into areas of the campus needing heating. The TES tank stores chilled water, which is produced by the conventional air-conditioning system during the night, and is then used to cool buildings during the day, when the highest demand is placed on the air-conditioning system.

Gillette Capital Corporation (Gaithersburg, Maryland, USA)

The addition of 1050 ton-hours of latent ice storage to this facility in August 1994 saved the building owners both initial system costs and subsequent operating expenses. The project cost just over US$121,000, with 57% of this expense paid for by utility incentives, including a US$350 per kW demand-reduction rebate. An air-cooled reciprocating chiller was originally used to cool the 5760 m^2 building, with the chiller operating 14–15 hours per day during the hottest summer months. With the full-storage system, the cooling load from 8:00 a.m. to 5:30 p.m. is now supplied by ice alone, with the chiller normally running only 5 h during the night to replenish the ice supply. The peak electrical load during the four-month summer peak period is reduced by 198 kW, avoiding the US$12.95 per kW demand charge, and resulting in over US$2500 in monthly operating savings. Accounting for initial financial incentives as well as operating savings, a simple payback period of 3.5 years is expected for the TES system.

Miller Electric Company (Appleton, Wisconsin, USA)

In 1990, this industrial manufacturer of welding equipment converted its cooling system from once-through well-water coolers and conventional rooftop direct-expansion units to ice thermal storage. Conversion eliminated the owner's concerns with the high sewer costs associated with the well-water units and the pending phase-out of the chlorofluorocarbons (CFCs) used in the direct-expansion units. The 46,450 m^2 of conditioned space has an air-conditioning peak design capacity of 3000 t. The cooling load is handled by 1380 t of ice harvesting equipment using ammonia as the refrigerant and operating on a weekly load-shift strategy in which ice is made only during the off-peak weekend and weeknight hours. The owner received a US$905,000 rebate from the local electric utility, and realizes a 65% (US$140,000) reduction in annual air-conditioning costs.

Kirk Produce Company (Placentia, California, USA)

In operation since 1987, two TES units are charged with 465 tons of ice cooling capacity during weekends and an additional 360 tons during off-peak weekday times. The ice is stored with 605.6 m^3 of water in a 1161.2-m^3 storage tank. The water at 0 °C is pumped from the tank through spray nozzles to cool air to 1 °C, for use in cooling fresh-picked strawberries prior to storage and shipping.

Beyond controlling humidity, which is vital to the preservation of strawberries, this process cooling system annually saves $153,000, or more than half of the refrigeration plant operating costs.

These case studies demonstrate that TES technology offers to owners and regions compelling energy savings as well as environmental, diversity, and economic benefits. As TES now seems poised for wider commercialization, institutional policies, such as those previously identified, should be considered for implementation to increase the market penetration of TES beneficially.

5.7 Concluding Remarks

The main advantages of using TES can be summarized as follows:

- Substantial energy savings can be realized by taking advantage of TES when implementing the techniques such as using waste energy and surplus heat, reducing electrical demand charges, and avoiding heating, cooling, or air-conditioning equipment purchases. These savings in energy can be realized despite the fact that the storage energy efficiency, the ratio of thermal energy withdrawn from storage to the amount input, is less than 100%. Storage energy losses are often small, for example, energy efficiencies up to 90% can be achieved in well-stratified water tanks that are fully charged and discharged on a daily cycle.
- TES plays a significant role in meeting society's needs for more efficient use in various sectors as it permits mismatches between supply and demand of energy to be addressed.
- With TES, peak-period demand for electrical energy can be reduced by storing electrically produced thermal energy during off-peak periods and using it to meet the thermal loads that occur during high-demand periods. For example, a chiller can charge TES at night to reduce the peak electrical demands experienced during the day.
- TES exhibits enormous potential for more effective use of TES equipment, and for facilitating large-scale energy substitutions economically. The economic justification for TES systems normally requires the annual income needed to cover capital and operating costs to be less than that required for primary generating equipment supplying the same service loads and periods. A coordinated set of actions is required in several energy sectors to realize the maximum benefits of storage.

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Study Questions/Problems

5.1 What kinds of energy-saving opportunities are offered by TES?

5.2 Compare the daily energy load profiles of a conventional building with no storage and full storage options.

5.3 Compare the economics (in terms of payback period) for a building in a local city if TES is introduced with full storage and partial storage. Estimate costs for a TES system at your location and utilize local utility rate structures.

5.4 How does TES contribute to resolving space limitations that may be present in a building?

5.5 Describe possible energy conservation strategies with TES.

5.6 Explain the major benefits of a cold TES.

5.7 What kinds of financial benefits are expected from TES?

5.8 In what situation might the main financial savings from introducing TES be due to reduced demand charges, rather than reduced energy consumption?

5.9 In what situation might the main financial savings from introducing TES be due to reduced energy consumption, rather than reduced demand charges?

5.10 Explain how a demand-side management option is used with TES for better savings.

5.11 Describe how one would determine if it is economically justified to use different sources of heat (industrial waste heat, solar thermal energy, cogenerated thermal energy, etc.) in a TES system for heating capacity.

5.12 Describe how one would determine whether it is economically justified to use different sources of cold (chiller generated, heat-pump generated, winter cold, etc.) in a TES system for cooling capacity.

5.13 Summarize the key advantages of using TES after reading the case studies.