THERMAL ENERGY STORAGE

Thermal storage is a method of storing heat for future use. Most often, thermal storage is used when future heat sources or sinks are either not available at a sufficient rate or will be more expensive. A common application of thermal storage is the domestic hot water heater. Most household water heaters use an electric resistance element or a natural gas burner as a heat source. A resistance element may supply heat at a rate of 6 kW, whereas a hot shower requires 20 kW to heat 6 L/min of water from 16°C to 40°C. Some amount of hot water must be stored in the tank because the element cannot heat the water at a rate sufficient for a shower or most other uses.

Heat is stored in the hot water tank to meet the demand for future use. The number or duration of showers possible depends upon the quantity of water stored and the tempera-

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ture at which it is stored. To meet the desired water temperature of 40°C with 60°C stored hot water, 3.4 L/min of hot water can be mixed 2.6 L/min with 16°C cold water. If the water is stored at 70°C, only 2.8 L/min of hot water is required.

As in the hot water tank example, the fundamental properties of any thermal storage system are the amount of energy stored and the temperature at which it is stored. If the temperature of the storage medium is below ambient conditions, it is a lack of heat (a heat sink) that is stored. Storage of a heat sink rather than a heat source can alternatively be called cool or cold storage. In either case, the potential to transfer heat to or from the sink or source depends upon the temperature and mass of the storage medium.

Heat is stored by raising the storage medium temperature or changing its phase (e.g., from solid to liquid) or both. Certain storage media may be better suited for a particular application depending upon their thermodynamic properties. The specific heat, c, of a substance is a property relating the quantity of energy stored or removed due to an increase or decrease in temperature (without a change in phase.) Specific heat is a temperature and pressure dependent property. However, most practical thermal storage media are used in a solid or liquid state where the variance of specific heat with pressure is negligible. Also, the change in specific heat over moderate temperature ranges can be neglected in many applications.

Materials with high specific heats are advantageous for use as thermal storage media. In many cases the volume occupied by the storage medium is of more concern than the weight. In these cases the specific heat-density product provides a better indicator in comparing alternative media choices. For example, aluminum has a specific heat nearly twice that of steel (0.9 kJ/kg-K vs. 0.5 kJ/kg-K), but because of their different densities, steel has a 60% larger volumetric heat capacity (2,454 kJ/m^3-K vs. 3,935 kJ/m^3-K). Water, at standard conditions, has a volumetric heat capacity of 4,175 kJ/m^3-K.

Phase change materials (PCMs) used in thermal storage applications are almost exclusively from solid to liquid or vice versa. Changing a liquid to the gas phase is accompanied by order of magnitude changes in volume (or pressure if the volume is held fixed) and storage facilities to handle such changes would be highly impractical to construct. However, compressed air energy storage has been used at a few electrical plants where underground caverns are used to contain the compressed air. The quantity of heat necessary to change phase from solid to liquid (or from liquid to solid) is commonly called the latent heat of fusion. For most substances, their latent heat of fusion is equivalent to the quantity of heat required for a large change in temperature of the substance in a single phase. Water's latent heat of fusion at atmospheric pressure (335 kJ/kg) is approximately 80 times greater than the heat associated with changing liquid water by 1°C (4.18 kJ/kg).

Chilled water storage systems (a heat sink or alternatively called a cooling source) have seen extensive use in building cooling systems. Usually, the cooling storage is used because the electricity used to operate the water chilling equipment (i.e., chillers) can be purchased at a cheaper rate during certain hours of the day. Chilled water storage is also employed when the building's cooling requirements sometime exceed the capacity of the installed chillers (1).

FUNDAMENTALS

To illustrate the application of thermal storage, consider the transport of energy, whether thermal, mechanical or electrical, from a source to a building cooling system as shown in Fig. 1. There may be a number of energy conversions (e.g., from thermal to mechanical to electrical) as the energy moves from source to the end use. The original source could be from the combustion of coal or natural gas, or from heat liberated in the fission of radioactive materials. It should be noted that

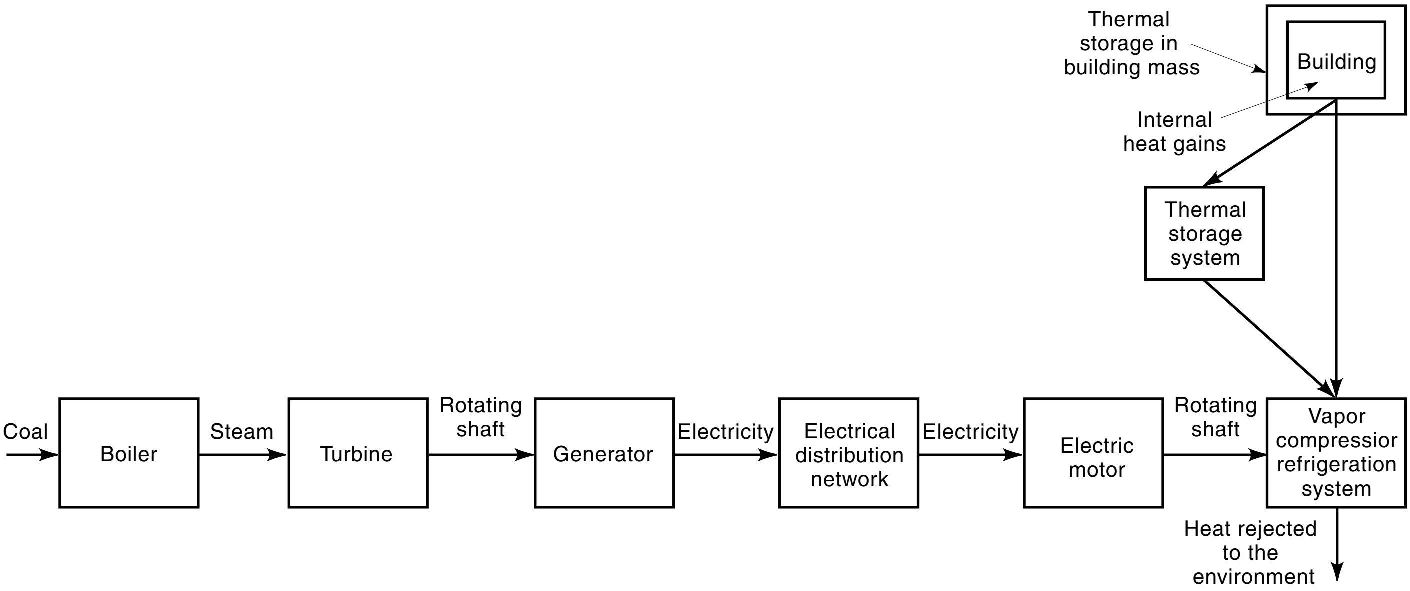

Figure 1. Without any intervening energy storage, the required energy must be simultaneously supplied through a chain of energy conversion processes.

the energy flows in the diagram are of "utilizable" energy which decreases in quantity at each conversion and transport process. The energy transferred from source to end use is conserved and, although not shown, significant quantities are transported to the ambient environment in each conversion and at the end process.

Without any intervening energy storage along the path shown in Fig. 1, the rate of energy transferred from the source and the rate of all energy conversions is directly linked to the rate of energy consumed by the refrigeration cycle. As the cooling load met by the refrigeration cycle increases or decreases, the source and all the conversions must respond immediately by increasing or decreasing their rate of energy transfer. (In any real energy conversion and transport system, e.g., an electrical generation and distribution network, there is some energy storage; however, the amount is very small in comparison with the quantity of energy transferred.)

With energy storage systems, the link of simultaneous energy generation, transfer and consumption can be decoupled. There are great economic advantages to decoupling the link. Without storage, all generation, conversion, and distribution equipment and facilities must be of sufficient capacity to meet the largest expected load (e.g., peak load). With storage somewhere between the source and the end use, not all equipment and facilities must be sized to meet the peak. Smaller equipment can be used with energy coming from storage during peak periods and energy stored during periods of low demand. Also, the cost of electrical energy generally increases with the rate (demand) at which it is provided. With a storage system energy can be stored over periods of lower cost and then be pulled from storage during periods of higher cost.

Different types of storage systems may be employed as the energy is transported from the source to the end use. Thermal energy storage is employed in transfers to or from a heat source or sink. Other energy storage systems include electrical and chemical energy storage (e.g., batteries and fuel cells) and mechanical energy storage (e.g., flywheels.)

The electrical energy transfers shown in Fig. 1 are used to operate a building's cooling system (i.e., a chiller.) The cooling system must remove heat from the building at a rate sufficient to keep the building's internal environment within a defined range of comfortable temperature and humidity. Some of the heat sources that contribute to the cooling load include heat conducted through exterior walls, heat from lighting inside the building, heat from building occupants as well as heat from personal computers and monitors. Also, fresh air used to ventilate the building must be cooled and dehumidified.

A building's exterior and interior mass constitute a thermal storage system. The rate of heat added or removed from the building mass depends primarily upon the weather (i.e., outdoor air temperature, incident solar radiation) and the building's internal air temperature. The interior temperature can vary over a relatively small range of comfortable interior temperatures during occupied hours and over a larger range during unoccupied hours. Thus the building mass can be employed as an active thermal storage system by controlling the interior temperature. Braun (2) discusses the control of building mass thermal storage as a means to reduce energy costs and peak electrical demand. Morris et al. (3) present results from experimental and simulated optimal control of building thermal energy storage.

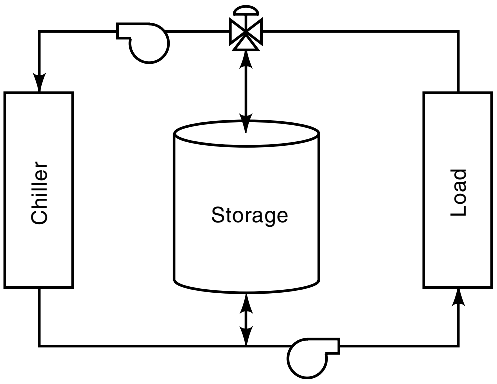

Figure 2. Schematic of a simple chilled water storage system. Depending on the flow arrangement, the chiller can charge the storage tank or (possible simultaneously) serve the load. Alternatively, the load can be served by the storage tank by itself or in combination with the chiller.

The schematic in Fig. 2 demonstrates the use of a thermal energy storage device between an energy source (or sink, as in the case of the chiller) and a heat transfer requirement or load. The load may be periodic, as in a building's cooling load, peaking during the day and reaching a minimum during the evening. An example cooling load profile over 2 days given by $q(t)$ is shown in Fig. 3.

Without the storage tank, to meet the required load the chiller must operate exactly in synch with the load trajectory. The opportunities for energy cost savings are limited to either reducing the load or increasing the operating efficiency of the chilling equipment. However, with the storage tank, the chiller operation can be decoupled from the load. With flow controls among the load, chiller, and storage tank, various modes of operation are possible. The full capacity of the chiller could be used solely to charge the storage tank or could simultaneously serve all or part of the load. Likewise, the storage tank could provide all of the load or some portion of the load with the chiller serving the remainder.

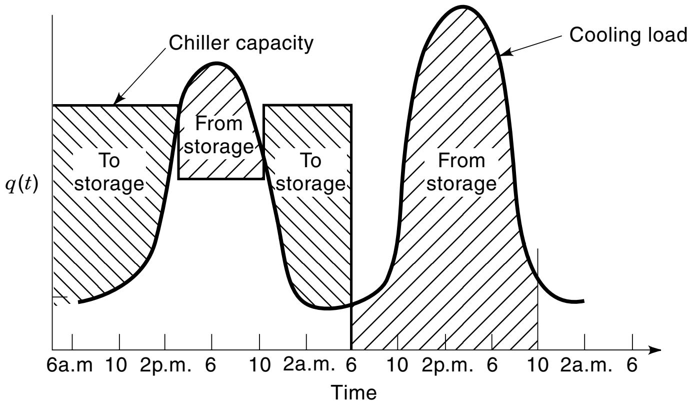

Figure 3. An example building cooling load profile over a 48-h period.

Usually, because almost all buildings will experience peak late afternoon loads in the summer, electrical utilities also experience peak demands that heavily task their generating and distribution resources. Accordingly, utilities have a time of day rate structure with relatively high costs during high-load hours and lower costs during low-load hours. With thermal storage, the chiller can run either solely or more often during the lower rate periods charging the storage tank to meet future loads that occur during the higher rate period.

In addition to time of day rates, utilities often assess a charge for the customer's largest electrical demand during some billing period (e.g., during one month.) Using thermal storage can also reduce electrical demand peaks. Usually, the storage is charged by running the chiller overnight when other major electrical systems (e.g., lighting, personal computers, etc.) are off, resulting in a reduction in the total building electrical demand. Also, the longer the time available to charge the storage tank, the lower the required chiller capacity (rate of charging) and therefore the lower the chiller power demand.

To charge the storage tank adequately for future load requirements, a predicted load profile must be assumed. If it is desired that the storage tank serve all of the load in Fig. 3 from 6 a.m. to 10 p.m. on the second day, the storage tank would need to be charged with a total capacity equal to or greater than the integrated load over the 6 a.m. to 10 p.m. time period.

APPLICATIONS

Chilled Water Storage

In many large cooling systems, heat is transported from cooling loads by chilled water. The chilled water is usually in a closed loop system where a refrigeration cycle provided the cooling source. A simple storage method is to use the chilled water as the storage medium. Typically, large water tanks are used to store the water (4). In some facilities the on-site water storage for the fire suppression system is used for chilled water storage.

As chilled water is drawn from a storage system, such as the tank in Fig. 2, an equivalent amount of warmer water from the load is added to the system. To have an effective chilled water storage system the colder chilled water must be separated from the warmer water it displaces. When a single tank is used for chilled water storage, the natural stratification of colder water at the bottom of the tank and the warmer water at the top can be employed as a separation method. In order to maintain a sharp vertical gradient in temperature (thermocline) between the warmer and colder water masses, steps must be taken to minimize mixing in the tank. Baffles may be placed in the tank to minimize horizontal mixing. Also, using many distributed inlet and outlet nozzles helps to minimize mixing as water is added or removed from the tank. Since water's density at standard atmospheric pressure is greatest at about 4°C, care must be taken to not charge the tank with water at or below this temperature.

Thermal storage tanks may also use a membrane (diaphragm) to keep the cold and warm water masses separate. The membrane can rise and fall as the tank is charged and discharged. The cold and warm water masses can also be separated using a series of smaller tanks or compartments. The colder chilled water is always drawn or added to the system at one end of the series and the warmer water added to or drawn from the other end.

Ice Storage

As with chilled water storage, ice storage uses the heat transfer fluid as the storage medium. However, with ice storage, the relatively high latent heat of fusion of water (335 kJ/k°C at 0°C) is utilized. Ice storage systems differ in the way the ice is formed and stored (5). In external ice-on-coil systems, ice forms on coils submerged in a water storage tank. Although the source of cooling in most ice storage systems is a refrigeration cycle, a secondary fluid rather than the refrigerant is circulated inside the coils. Typically an ethylene glycol and water mixture is used as the secondary fluid. In external ice-on-coil systems, ice is built up on the coils, growing as thick as 7 cm. The water in the tank is aerated or otherwise agitated so that the ice forms on the coils uniformly. Excessively thick ice formation creates ice bridges, restricting water circulation around the coils and impeding heat transfer.

When building ice externally on the coils, a thickness limit is imposed, as the increasing thickness of the ice tends to insulate the coil. A colder coolant temperature inside the coils is required to continue forming ice as the thickness increases. The lower coolant temperature requires the refrigeration system evaporator to operate at a lower temperature and consequently reduces cycle efficiency.

In discharging the ice storage, warmer water is circulated about the coils, melting the ice from the outside of the formation (external melt).

In internal melt ice-on-coil systems, the secondary heat transfer fluid is used in charging and discharging modes. In the charging mode, the secondary fluid circulates between the coils in the tanks and a heat exchanger coupled with the refrigeration system evaporator. In discharging the store, the secondary fluid is rerouted through another heat exchanger coupled with the cooling water loop that serves the cooling load. The ice melts from the inside (at the coil external surface) as the secondary fluid exchanges heat from the cooling water to the ice storage tank. The internal melt system is advantageous over the external melt system because the refrigeration cycle does not have to operate at the lower temperatures needed to freeze water on the outside of the formation.

Ice harvester systems use a separate tank to store the ice (6). Ice is built up in cycles on the external surface of a vertically positioned refrigerant evaporator. After building up a certain thickness of ice on the coils (approximately 0.5 to 1.0 cm), the refrigerant is valved such that the hot gas from the compressor enters the evaporator for a short period of time. The hot gas melts a thin film of ice at the evaporator external surface causing the ice build-up to fall into an ice storage tank below. Alternatively, in some systems the ice is scraped away mechanically. Chilled water is pumped from the storage tank to the heat exchangers serving the cooling load, then back over the evaporator coils.

Other systems use small containers of water (e.g., plastic balls filled with water) to store ice. The method of freezing and melting the ice is similar to the internal melt on coil storage systems. A secondary heat transfer fluid is circulated around the water-filled containers and the refrigerant evaporator when freezing the ice. During the melting cycle, the secondary fluid is circulated around the containers and another heat exchanger coupled with the chilled water loop serving the cooling load.

Phase-change materials (PCMs) other than water may also be used in cool storage systems (7). Typical building air conditioning systems use approximately 7°C water in coils to cool air flows from approximately 24°C to 13°C. Using a PCM with a phase-change temperature of approximately 6°C rather than water at 0°C allows the refrigeration cycle to operate at a warmer evaporator temperature and therefore use less energy input per kilojoule of cooling. Typically mixtures of inorganic salts and water having phase change temperatures near 8°C are used in encapsulated containers.

Some building air conditioning systems that use ice storage (at 0°C) take advantage of the cooler thermal sink and circulate smaller amounts of relatively low temperature air through the building (1). The lower temperature air conditioning system uses relatively smaller duct work and less fan energy. Because the low temperature air can cause fogging or unwanted condensation and be poorly distributed if introduced directly into a room, the cold air is usually mixed or entrained with warmer air before being blown into the space.

Solar Heating Systems

Some means of thermal storage is required in solar heating systems as the availability of solar energy is seldom in synch with heating requirements. Solar heating systems are generally classified as passive or active systems. Passive solar heating systems rely on natural circulation in transporting heat to storage whereas active systems use forced circulation (i.e., utilizing pumps or fans).

Solar water heating systems, active or passive, typically use water storage tanks for thermal storage. Simple domestic solar water heating systems may use existing electric or natural gas fired water heaters for storage. When solar energy is insufficient to meet the water heating load, the electrical element or natural gas burner will maintain the hot water supply. With an air/water heat exchanger, solar water heating systems can also serve air heating loads.

Various passive solar heating systems may be employed to store some amount of incident solar energy during the day for use overnight (8,9). A large area of glazing (windows) on the south face of a building (in the northern hemisphere) can be combined with an interior wall facing the glazing. During the daylight hours, incident solar energy warms the wall to the extent that the wall cools and warms the air in the house during the hours of darkness. Heat transfer from the wall to the air in the house is primarily by convection and in some cases the air flow can be controlled to minimize losses during the storage period and to enhance heat transfer during the discharge period.

Electric Heat—Rockbed Storage

Rockbed thermal storage systems are usually employed in conjunction with electrical resistance household heating systems. With time-of-day electrical rates (on-peak and off-peak pricing), the thermal storage system can heat the rock mass during the lower rate period for discharge during the high-rate period. The primary advantage of the electrical resistance heater/rockbed combination is the ability to use off-peak electricity. The rockbed storage is typically used in regions with long periods of subzero weather where air source heat pumps are not advantageous over resistance heat. Also, in the extreme cold climates, electrical utility peaks occur during the early morning hours of extremely cold days. The rockbed is charged during lower rate off-peak periods in the daylight hours and discharged at night.

Building Mass Thermal Storage

Building mass can also be utilized for thermal storage (10). The building structure and internal elements such as floor slabs and walls become the storage media used in conjunction with the building's air conditioning system. During the night, the building may be precooled to a limited extent using the air conditioning system and cool outdoor air if available. Lower electrical rates can be taken advantage of when operating the refrigeration system during the night. Also, because the night air temperatures are usually cooler than the day, the refrigeration systems run more efficiently rejecting heat to the cooler outdoor air.

There are practical limits on using a building's mass for cooling storage. The building's internal surfaces should not be so cool that occupant comfort is decreased or so cool that there is a possibility of condensation on surfaces when ventilation air is brought into the building. However, because of the large building mass, even a few degrees of decreased building mass temperature can contribute to decreasing cooling requirements during the day. The use of PCMs in the building materials, such as wallboard, is a method of increasing thermal storage capacity while limiting temperature changes.

Turbine Inlet Cooling

Many electric generating utilities use gas turbines to help meet peak loads. Installing a gas turbine peaking plant is often more economical for a utility than investing in increasing larger base load plant capacities even though the gas turbine may have a higher cost-per-kilowatt-hour rate. Warmer weather, which contributes to higher electrical demand, also reduces the power available from a gas turbine.

A gas turbine can lose 25% of its generating capacity as the air inlet temperature increases from 15°C to 38°C. During the peak demand periods, it is the plant's capacity and not the cost of energy that is of the greatest value. Ice storage systems have been employed to precool turbine inlet air during peak load periods (11). Electrical energy from the same turbine or any other source on the grid is used during off-peak hours to build the ice store. Although the overall cost per kilowatt-hour may be increased with the investment and operation of an ice storage/inlet air cooling system, the increase in available capacity is usually of greater value to the generating entity.

DESIGN

Thermal storage systems may be designed to meet all or part of a given load over some period of time. For example, in chilled water storage systems, the water storage tank may be sized to meet all the building's cooling load during occupied hours with the chiller system charging the entire store overnight. Alternatively, in a situation where the building's chilling system is undersized, a thermal storage system may be sized only to meet the difference between the building's peak cooling load and the undersized chiller's capacity.

Storage size can be determined by assuming a load profile that must be met and the capacity of the thermal energy source. An example cooling load profile over a 48-h period is shown in Fig. 3. One possible profile for operating the chiller is also shown. The quantity of energy storage required is indicated by the integrated area below the required load curve and above the available chiller load curve. In order to charge the store, the integrated area where the chiller capacity exceeds the required load must exceed the area indicating storage.

With thermal storage, the chiller is decoupled from the load and can have almost any profile of operation so long as the integrated area associated with charging the store exceeds the area associated with storage discharge. However, there is at least one profile of chiller operation that minimizes energy costs over the subject time period. The storage indicated by this optimal chiller operation profile is the optimal energy storage requirement over the subject period. But for a valid economic analysis, operation over a longer period, such as the anticipated life of the system, along with equipment costs must be considered.

Models of the thermal storage system, chiller system, and predicted load profiles can be used to estimate operating costs over a given period of time. Weather data used in the simulation can be real measured data or meteorological data which simulates a typical year. Various storage charging and discharging schedules along with various storage sizes and chiller capacities can be simulated to determine an optimal storage size.

Electrical rates that differ depending on the time of day are usually the primary influence in determining the optimum tank size as well as in determining the best operating schedule (or profile) for charging and discharging thermal storage systems. Before deregulation of electrical utility systems in the United States, a common electrical rate structure applied to commercial or industrial customers included time of day rates (usually one "on-peak" rate and one "off-peak" rate) for energy use (kW-hr) and a demand charge for the highest rate of energy use (kW) over some billing period. More recently, industrial and commercial users have been able to choose real time pricing (RTP) for their electrical rate schedule. In RTP, electrical energy rates vary each hour according to electrical market supply and demand.

Optimum tank size and storage operation under RTP can differ significantly from optimal values under a time of day rate structure. For example, if RTP rates are significantly lower over a weekend, it may be economically advantageous to have a storage system capable of meeting loads over more than one day. Daryanian and Bohn (12) investigate and compare optimal sizing of storage systems under both RTP and time of day electrical rates.

High temperature thermal storage systems may also be designed for use by electrical generation plants. Somasundaram et al. (13,14) investigate the application of thermal storage in power plants as well as applications in cogeneration systems.

OPERATION

A simple operating strategy is to charge the store over one period (when the heat source or sink is available at a sufficient rate or at relatively low cost) and discharge it over another. However, in most thermal storage systems, the rate and duration of charging and discharging the store can be controlled. To maximize the benefits of thermal storage, an optimal control strategy that minimizes cost or some other desired criterion should be employed (15).

In some cases, when the heat source or sink either will not be available in the future or will be available only at great cost, the optimal strategy is obvious. In a solar heating system, the incident solar energy is free, and, if the heating requirement exceeds the maximum amount of heat storage, the store should be charged as much as possible. If the on- and off-peak rates of an electrical rate structure differ by orders of magnitude, a chilled water system should be charged fully (or at least to some amount greater than the expected next day's cooling load) when the lower rate is available.

In most applications, the best or optimal control strategy is not entirely obvious, but may be determined through simulation or other analysis. A general outline of an approach using simulation follows:

Develop a model of the system including the storage unit and the load served by the store. Often weather-dependent or otherwise time-varying loads can be predicted using statistical models.

Identify controlled variables such as the mass flow rate of the fluid entering the store. Identify the external time varying uncontrolled variables such as the predicted heat-transfer load to be served by the storage system. In some cases the thermal loads may be calculated from a building model where the external variables will include the outdoor weather conditions.

The model should reasonably agree with the actual process. Model parameters, if present (such as rate parameters), can be determined using measured data for processes already operational. If measured data are not available, manufacturers frequently provide performance data in tabular or graphical form.

Define the objective function to be minimized, such as electrical costs over a given period. The cost function should include time varying rates if applicable.

Identify constraints on the control variables and any model-dependent variables. For example, a particular piece of refrigeration equipment may only provide chilled water between a defined lower and upper limit on temperature.

Create a computational model of the combined system, storage unit, and load. The computational model should take as input, predictions of the load profile as well as time varying values of the controlled variables. Model output should include calculated values of the objective function over time.

Use an optimal control algorithm such as dynamic programming that can determine a trajectory of control variable values that minimizes the objective function (e.g., energy costs) over a particular time period (e.g., 24 h). Although a study period of 30 days may produce a particular minimum energy cost, shortening the time period (i.e., horizon) to 24 h, for example in a building cooling storage system, could greatly decrease the difficulty of the problem solution while only slightly degrading the results (15).

CONCLUSION

In the United States as well as other industrialized nations, electric utilities have been converted from government- or investor-owned regional monopolies to open market competitors. In an open market, electrical energy is a commodity priced according to its supply and demand. However, unlike most other commodities, marketed electrical energy is not stored in any significant quantities.

Although electrical energy is not normally storable by electricity consumers, with thermal storage, relatively lower cost electricity available during low-demand periods can be used to generate or transport heat into sources or sinks for use during periods of higher demand and cost. As the number and capacity of thermal storage systems increase, the large variations in electrical demand will decrease and therefore the predictable difference in rates for on-peak or off-peak usage will decrease. The influence of an open market electricity supply on the installation of thermal storage systems is considered by Caldwell and Bahnfleth (16).

This article has presented the basic uses and operation of thermal energy storage systems. In addition to the applications listed, there are other unique thermal storage systems including those used in storing high-temperature heat sources used in power generating cycles (17). Although the media (typically molten salts) and temperatures in power cycle thermal storage are significantly different than chilled water or ice storage, the fundamental use and operation of the thermal storage is the same.

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