Rev Chem Eng 28 (2012): 81–99 © 2012 by Walter de Gruyter • Berlin • Boston. DOI 10.1515/revce-2011-0018

# Optimization and advanced control of thermal energy storage systems

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## Abstract

This paper reviews the optimization and control of thermal energy storage systems. Emphasis is given to thermal storage applied to combined heat and power systems, building systems, and solar thermal power systems. The paper also discusses how applications of thermal storage can benefit the chemical industry. Optimization of the design and control of thermal storage systems improves plant performance and improves the management of transient energy loads in a variety of applications. In order to maximize the benefits of thermal storage, it is necessary to include advanced multivariate constrained controls, such as model predictive control. Thermal storage also increases system flexibility, allowing the incorporation of intermittent renewable energy sources. The flexibility of thermal storage will play an increasingly important role as utilities implement smart grid technology with time-of-use electricity pricing. Lastly, thermal energy storage improves system economics by reducing required equipment sizes, improving efficiency, and reducing equipment wear.

**Keywords:** buildings; combined heat and power; model predictive control; optimization; solar thermal power; thermal energy storage.

## 1. Introduction

Rising energy prices and the possibility of greenhouse gas emission regulations have made energy efficiency essential to all industries. The electric power sector has historically dealt with rising demand for electricity by building new power plants. Because this demand fluctuates on a daily basis, however, much of the installed power capacity goes unused because it is sized to meet peak electrical loads. Therefore, during off-peak hours, this equipment may sit idle. Furthermore, "peaking" power plants are usually inefficient because they are designed to have low capital costs as they will only be used for a fraction of the time. The paradigm of building generation capacity to meet peak demand, however, may be changing, if only slightly. Energy storage technologies could help electric utilities level their electric demand by allowing consumers (or suppliers) of energy to shift the times that electricity is used. For instance, energy can be stored during off-peak times and dispatched during peak times, thereby reducing the peak generation that a utility must have. In order for energy storage to make a significant impact, inexpensive storage technologies, which can be implemented on a large scale, must be developed. Thermal energy storage (TES), the storage of heat or cooling, has the potential to make such an impact.

Because TES stores energy in one of its basest forms, it is a relatively simple technology. It is this simplicity, however, that gives TES the potential to be a very inexpensive, yet impactful, technology. For example, TES can have an immediate impact on capital costs by replacing expensive chilling or power generation equipment with a much less expensive storage tank. TES will also provide ongoing operating cost savings by allowing the system to shift times of consumption (production) of energy to off-peak (on-peak) times. Therefore, TES systems can dramatically reduce payback periods in addition to improving the project's return on investment.

Many of the benefits of TES could also be realized in the chemical industry. A key to energy efficiency in the chemical industry is waste heat recovery, wherein waste heat is extracted from one process and delivered to another in an effort to reduce energy consumption. With TES, heat integration can be done dynamically, where excess heat can be stored at one time and delivered at another. Because chemical processes are typically energy intensive (many even have their own electricity and heat generation facilities), TES has significant potential to improve energy efficiency and provide great cost savings in the chemical industry.

Because systems that use energy storage and the storage itself are inherently transient, it is critical to develop effective operating strategies for using TES technologies. This work provides a review of research that has taken place in TES with a particular emphasis on modeling, optimization, and control. It is focused on three main areas in which TES has found widespread use: combined heat and power systems, building systems, and solar thermal systems.

## 2. Overview of TES

TES is the storage of heat or cooling for later use. Because TES involves storing energy in one of its most primitive forms, it is a technology that has been used for centuries. Its simplicity has allowed it to become a successful energy storage technology. TES is typically a very cost-effective method of storing energy, especially when compared to storage technologies that rely on expensive, sometimes exotic materials, like battery storage. As a consequence of its simplicity, however, TES is not quite as versatile. Therefore, intelligent ways to use TES must be developed so that this promising, cost-effective technology is effectively applied.

Thermal energy can be stored as sensible heat (where heat is stored simply by changing a material's temperature), latent heat (where heat is stored by changing a material's phase), or chemical heat (where heat is stored in reversible, endothermic reactions and recovered by the corresponding exothermic reaction). TES can be classified as active or passive. In active systems, a fluid is circulated in order to collect and distribute heat (e.g., hot water flowing from a tank to heat a building). In passive systems, the storage medium and delivery system are stationary and are built into the system (e.g., the thermal mass of a building).

TES systems can use any phase (solid, liquid, or vapor) as a storage medium. Often, multiple phases may be used, such as in pebble bed storage where a fluid passes through a packed bed of solid particles in order to transfer heat to the particles. Latent heat storage also uses the transformation of the medium between phases so that energy can be stored using the material's heat of fusion (solid to liquid) or heat of vaporization (liquid to vapor). The development of phase change materials (PCMs) for heat storage is an active research field. PCMs are materials designed to change phase at a specified temperature. For example, one application of PCMs is embedding such materials into a building to increase the building's thermal mass so it can be used for passive heat storage.

TES can be used to shift electrical, heating, and cooling loads and has found popularity in a wide variety of applications. TES is widely used in district cooling, where multiple buildings in a region share a cooling loop and a central chilling station. This setting, which takes advantage of the economies of scale, uses a central TES system (typically with chilled water or ice as a storage medium) to lower electricity costs by chilling the water during off-peak hours. This stored energy is then used to offset peak cooling loads the following day by using the stored energy, rather than the chiller. Combined heat and power (CHP) systems, where electric power and heat are generated simultaneously, are frequently used in district heating or cooling, making these applications a good candidate for TES as well. If cooling, heat, and electrical loads do not coincide, TES can be used to store the heat or cooling to help better align these loads. TES has also found application in solar energy. TES can be used to store the sun's energy as heat, which can be used for space or water heating in buildings. TES can be used in solar thermal power applications, taking an intermittent source of energy, such as the sun, and converting it into power that can be readily dispatched as needed. Thus, TES is a cost-effective technology, which has proven valuable in a wide variety of applications. For further reading regarding TES overview, see Dincer and Rosen (2011).

## 3. Overview of control strategies

Because systems that require storage exhibit transient behavior and the storage processes themselves are transient, selection of appropriate control strategies is critical. In some cases, single-input-single-output (SISO) control can be used. SISO systems use only one input to manipulate a corresponding output. SISO control can be carried out using measurements of the process output (feedback) and using that output in an algorithm to determine the prescribed input. The most common algorithm is the proportional-integral-derivative (PID) controller (or variants thereof), where the magnitude, integral, and derivative of the error between the measured output and its desired set point are used to determine the input. For processes where inputs and outputs are highly coupled, multiple-input-multiple-output (MIMO) controllers can be used. Feedback control can also be implemented on a MIMO basis, although the PID algorithm will no longer be valid. MIMO controllers take a more holistic approach where a combination of output signals is used to determine the prescribed inputs. If disturbances to the system can be measured, feedforward control can be added to give the system the ability to reject measured disturbances in advance, without having to rely entirely on feedback measurements.

When system dynamics are too complex for a simple feedback control algorithm to be adequate or when there are process operating constraints, advanced control methods are needed. These advanced control methods often use optimization in order to handle the additional complexity and constraints (Edgar et al. 2001). Much research has been done in the field of advanced process control, resulting in a wide variety of control techniques. Among these techniques, model predictive control (MPC) has found widespread use. In MPC, a model of the system is used to make predictions of system performance and determine the inputs that result in optimal performance. Many variants of MPC exist, based on the type of model used, performance index, etc. Because MPC is the most widely used advanced control technique for systems with TES, it is highlighted in this paper. However, other optimization and control topics are also covered, including optimal system design and dynamic optimization.

## 4. Combined heat and power and TES systems

### 4.1. Introduction

Combined heat and power (CHP), also known as cogeneration, is the concurrent production of electricity and thermal energy from a single energy source. In a conventional system electricity is generated at a power plant (usually operated by the local utility) and the waste heat from the system is vented via cooling towers or ponds. Facilities that obtain electricity from these power plants must then use additional energy to provide their heating or cooling. Thus CHP has a major advantage over the traditional systems because it can utilize the waste heat from the electricity generation to meet the heating and cooling loads (via absorption chillers) of the facility (Figure 1). There are many variations of CHP, such as trigeneration or combined cooling, heating, and power (CCHP) and building combined heat and power (BCHP) (Wu and Wang 2006), but for this paper all variants of CHP will be grouped into the general CHP category.

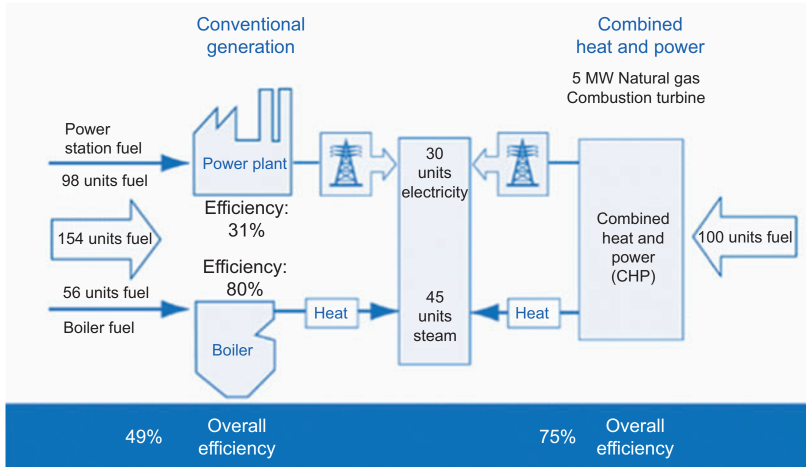


**Figure 1** Conventional energy supply system (left) vs. combined heat and power (right) (Environmental Protection Agency 2007).

Combined heat and power is not a new technology in the manufacturing industries. In paper manufacturing, for example, over 40% of the required electrical power was generated using CHP as of 2006 (see Figure 2). In other industries, however, CHP is far less prevalent. CHP coupled with TES is even less common. Therefore, there is significant potential for further adoption of CHP and TES to increase the energy efficiency of manufacturing plants.

In many cases, CHP potential is limited because of the difficulty of matching electrical and thermal demands. Thermal energy storage can be coupled with CHP to provide economic and energy savings, system flexibility, and system feasibility (see Figures 3 and 4) (Lai and Hui 2009). These systems will be referred to as CHP-TES systems. Thermal and electrical loads can be decoupled to some extent by adding TES to a CHP system. This has grown increasingly important as peak loads have grown, increasing the gap and variation in on-peak and off-peak electricity market prices. Proper design and control is necessary to realize the maximum value of a CHP-TES system. A review of optimization in CHP systems without thermal storage was recently published (Chicco and Mancarella 2009). This section focuses solely on CHP-TES systems.

Modeling of CHP systems has been performed using a variety of methods and a plethora of software packages. Hinojosa et al. (2007) reviewed some of these software packages, both commercial and custom, that are commonly used for modeling CHP-TES systems. CHP models can be as simple as a model of the CHP prime mover (typically a gas or steam turbine) to meet required electrical and heat demands for a few design days or as complex as a large system model describing not just the prime mover but also electrical and thermal loads, thermal storage, chillers and boilers, and the distribution systems. Other considerations in CHP-TES models include an appropriate time step, the ability to export electricity, the ability to model the utility rate structure, $CO_2$ saving projections, the ability to calculate required financial indicators [e.g., net present value (NPV), internal rate of return (IRR), payback period], and the ability to accept different fuels. It is important to choose a model with the appropriate complexity for the project requirements. CHP systems that will be providing relatively constant electrical or thermal loads do not require as extensive a model as a system with many integrated components that have significant interdependence and fluctuating demands.

The design and operation of a CHP-TES system is often sufficiently complex that researchers apply optimization in order to maximize project economics (Zhao et al. 1998). Henning (1998) discussed a number of optimization models that have been created for handling CHP systems with storage. Numerous researchers have investigated the best ways to address the optimization problem, which is generally formed as a mixed integer

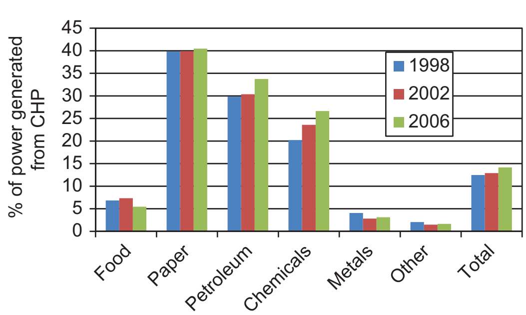


**Figure 2** Percent of total electrical power usage generated from CHP, by industry [Energy Information Administration (EIA) 1998, 2002, 2006].

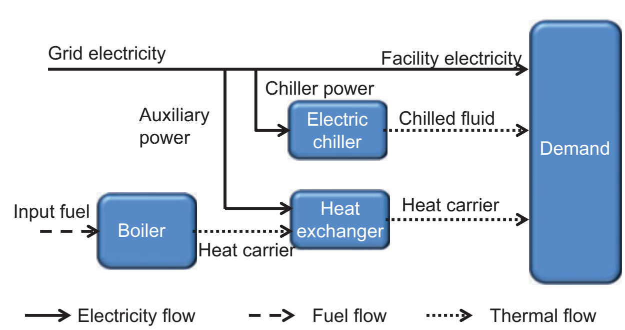


**Figure 3** A typical configuration for a conventional system. Adapted from Wang et al. (2010b).

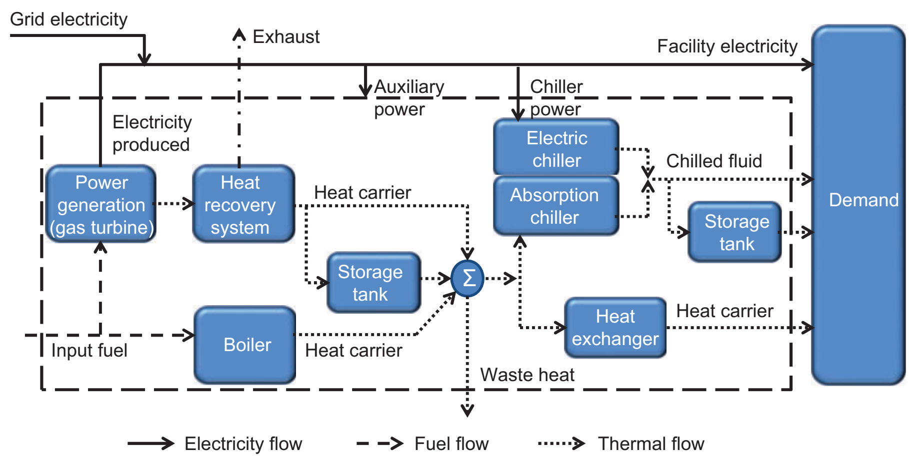


**Figure 4** CHP-TES system. The power generation is typically a gas turbine, but it could be a fuel cell, steam turbine, or other device that generates both heat and electricity. Adapted from Wang et al. (2010b).

linear programming problem (Ito et al. 1992, Yokoyama and Ito 1995, 2000, Rolfsman 2004, Houwing et al. 2009, Lozano et al. 2010, Wille-Haussmann et al. 2010), though it has been formed as a linear programming problem (Henning 1998, Lee et al. 1999), a nonlinear programming problem (Caldon et al. 2004), and a mixed integer nonlinear programming problem (Azit and Nor 2009). Sancho-Bastos and Perez-Blanco (2005) formed a linear quadric (LQ) problem with the solution provided by a linear quadratic regulator (LQR). CHP-TES optimization focuses on two aspects: the optimal CHP-TES operation and the optimal CHP-TES design (with emphasis on equipment capacity). Both aspects are highly dependent on the requirements of the system and on the electricity rate structure. If the electricity rate structure is not defined (such as with electricity spot market prices), this requires the prediction of the electrical prices (Rolfsman 2004). Because there will always be model uncertainties and errors in predicted values (in the case of Rolfsman there was a 35% decrease in system value because of imperfect predictions), it is important that optimal controllers are closed-loop (Sandou et al. 2005).

### 4.2. Conventional operation strategies

Ristic et al. (2008) described the following conventional operation strategies for CHP systems with or without TES.

1. **Electricity base load:** In the design phase the CHP unit is scaled to only meet the base electrical load. The CHP unit then runs at full capacity all the time. This has the advantage of operating the equipment at its most efficient operating point. However, it cannot take advantage of changing electricity prices or variations in thermal loads.
2. **Heat demand following:** The CHP system follows the heat demand and electricity is treated as a beneficial by-product. This strategy may reduce auxiliary boiler requirements and ensures that there is never surplus heat that is wasted. It cannot take advantage of changing electricity prices, and may in fact be negatively impacted by the price variation (if heat production is high when electricity prices are low it may be more economical to operate a boiler to meet the heat load).
3. **Electricity demand following:** The CHP system follows the electricity demand and the heat is treated as a beneficial by-product. This strategy is typical when electricity export is not allowed. It also allows the facility to "island" (i.e. operate independent of the power grid), because all electricity can be produced on site.

### 4.3. Objective function

The objective functions used for CHP-TES optimization vary considerably, but most objective functions follow the standard "costs minus revenue" form. The variation between objective functions generally comes about with which specific costs are considered as part of the objective function. In general the problem is formed as

$$J=\min \{C_{fuel}+C_{elec,pur}-C_{elec,sold}\} \tag{1}$$

where $C_{fuel}$ is the cost of fuel consumed by the CHP unit and any auxiliary boilers or electricity-only generation units, $C_{elec,pur}$ is the cost of any purchased electricity (which may include demand charges as in Azit and Nor 2009), and $C_{elec,sold}$ is the revenue generated from selling electricity to the grid. The objective function is minimized subject to constraints such as heating or cooling loads, equipment capabilities (such as maximum or minimum capacities), and in some cases legal constraints (e.g., Lozano et al. 2010). Constraints can be imposed as equality or inequality constraints. A requirement that electricity production matches demand would be an equality constraint while an inequality constraint would be, for example, the operating range for specific equipment.

Simple variations to the objective function given in Eq. (1) include adding the cost of water (Azit and Nor 2009), adding a penalty term for violating space heating or cooling comfort rules (Collazos et al. 2009), including staff and maintenance costs (Wille-Haussmann et al. 2010), adding an electrical standby cost (a cost paid to the utility for providing permanent backup power) (Azit and Nor 2009), including a cooling tower heat rejection cost (Lozano et al. 2010), including a plant energy self-consumption term (Bogdan and Kopjar 2006), adding a static transmission efficiency term for electricity exchanged with the grid (Lai et al. 1998), and including a cost relating to storing energy (Rolfsman 2004). In some cases the capital costs of the CHP-TES system were considered along with the operating costs. Lozano et al. (2010) used an objective function that included the fixed costs plus variable costs, or in other words the equipment amortization and maintenance costs plus a modified operating cost function as given in Eq. (1). Bruno et al. (2010) maximized return on investment (ROI) and thereby included both fixed and variable costs. Piacentino and Cardona (2008) formed a similar objective function, only they maximized NPV rather than considering ROI. Note that constants added to the objective function (e.g., fixed capital cost) do not affect the optimal solution.

Wang et al. (2010b) used the following for their objective function:

$$J=\max\{\omega_1 R_{energetic}+\omega_2 R_{economic}+\omega_3 R_{environmental}\} \tag{2}$$

where $R_{energetic}$ is the ratio of energy savings compared to a conventional system, $R_{economic}$ is the ratio of economic savings compared to a conventional system, $R_{environmental}$ is the ratio of environmental savings (measured as $CO_2$ emissions) compared to a conventional system, and $\omega_1$, $\omega_2$, and $\omega_3$ are weighting factors. The authors used an equal weight method (i.e., $\omega_1=\omega_2=\omega_3=1/3$). In this way they were able to optimize their system based on all three conditions. Shifting the weights to give one factor preference gives the user more flexibility in examining the "what ifs" of a system. Using weights in the objective function was also performed by Rolfsman (2004). He used the inverse of the equipment efficiencies as weighting terms for the fuel consumption of each unit.

Kostowski and Skorek (2005) introduced two objective functions, thermodynamic and economic. The thermodynamic optimum was defined as the lowest peak boiler usage, so the objective function minimized the peak boiler usage. The economic objective function was to maximize the change in net present value, or the increase in net present value from adding TES versus the no storage case. The economic optimal TES volume was 38% smaller than the optimal thermodynamic volume with a 27% shorter payback period.

In the majority of cases reviewed, the objective function was applied to an entire year, but the way in which the year's data were compiled varied significantly. As little as three days were used to represent a year, one day for each of the three relevant seasons (Bogdan and Kopjar 2006), while others used 365 distinct days (Rolfsman 2004). The climate affects the choice of the appropriate number of unique days. For example, Azit and Nor (2009) stated that in Malaysia the annual facility load can be represented by a single week of typical hourly loads since the climate is fairly constant year round.

### 4.4. Optimization techniques

Optimal solutions to both the design and operation problems have been found using dynamic programming (Ravn and Rygaard 1994, Maifredi et al. 2000), Lagrangian relaxation (Dotzauer et al. 1999), evolutionary programming (Lai et al. 1998), branch and bound method (Collazos et al. 2009), sequential quadratic programming (Sandou et al. 2005), particle swarm algorithm (Wang et al. 2011), decomposition method (Yokoyama and Ito 2000), simplex method (Frankovic et al. 2004), reduced gradient algorithm combined with a quasi-Newton algorithm (Zhao et al. 1998), generalized reduced gradient method (via Microsoft Excel's Solver) (Bogdan and Kopjar 2006), and Newton-Raphson combined with the conjugate method (Azit and Nor 2009). The optimization technique used may influence the optimal solution, but if the optimization problem is convex then an optimum is guaranteed and will be global. In that case the choice of the optimization technique will largely be affected by computation time, ease of implementation, ability to handle required constraints, etc. For solving non-convex problems, the choice of a solver may be more important. In some cases, however, the quality of the solution may be largely independent of the algorithm used. For example, Wang et al. (2010b) showed that the optimal solution from a particle swarm algorithm produces 1% greater savings than using a genetic algorithm. More information on optimization techniques is readily available in a variety of textbooks and other material (e.g., Edgar et al. 2001, Antoniou and Lu 2007).

### 4.5. Applications

Because the design and considerations of a CHP-TES system are dependent on the specific application, the most common CHP-TES applications will be reviewed separately. They include district heating and cooling, building heating and cooling, and integration with renewable energies. These three applications tie directly into chemical process facilities: plants often have some sort of district heating or cooling system to integrate heating and cooling streams, plants contain buildings which are heated or cooled, and introducing renewable energies correctly into plants is a valuable energy sustainability measure.

**4.5.1. District heating and cooling** There is more attention given in the literature to CHP-TES systems in district heating and cooling networks than any other CHP-TES system, nearly all of which emanates from Europe. In district heating and cooling networks that incorporate CHP, the CHP units produce electricity and use the waste heat from the electricity production to meet heating or cooling loads. Typical standalone CHP units are generally operated using the heat demand following strategy. This means that CHP units may be producing large amounts of electricity (because thermal loads are high) during off-peak hours when electricity prices are low, thus reducing revenues. It also means that during on-peak hours, when electricity prices are highest, CHP units may either have to run at partial capacity (because of low thermal loads) or run at full capacity and waste the excess heat. Additionally, because the CHP units are required to follow a changing thermal load, they will not always be operating in their most efficient operating region (i.e., at or near full capacity). Thermal energy storage, almost exclusively in the form of chilled or hot water, has been applied to address these issues.

Thermal energy storage has been shown to add significant economic savings to a CHP plant by taking advantage of the electricity rate structure. Bogdan and Kopjar (2006) modeled the addition of a hot water TES to a CHP system on a district heating network in Croatia and found that TES increased the plant's net income by 17% compared to the CHP-only system under a dual-time electricity tariff (i.e., where different rates apply for on-peak and off-peak times). The savings came from maximizing electricity production during peak electrical times (thus garnering the higher electricity market price) and storing the excess heat in the TES. At night with the low electricity prices, the CHP system would shut down and thermal loads would be met by the TES. This resulted in a net decrease in annual fuel consumption and electricity production as compared to the CHP-only case (i.e., the increase in on-peak production was less than the decrease in off-peak production). The decrease was allowed because the CHP-TES unit was not contracted to supply a set amount of heat or electricity.

Fragaki et al. (2008) found that for the UK, with the large difference between night and day electricity rates, TES can more than double the return on investment of CHP plants when measured in terms of net present value. They also determined that TES is still economical even if the electricity or gas prices change. In a sensitivity analysis they found that TES is economical up to a 15% reduction in average electricity prices or a rise in natural gas prices by more than 15%, although optimal size of the TES and the resulting NPV varied as prices changed.

Streckiene et al. (2009) found that TES allowed the CHP units to run at full load for longer amounts of time, thus increasing system efficiency (a finding also pointed out in Serra et al. 2009). They also found that the more variation there is in electricity spot market prices (e.g., the more the price changes), the more favorable CHP-TES systems are. Streckiene et al. reported more sensitivity of CHP-TES plants to fuel and electricity prices than did Fragaki et al., even to the point of the TES becoming uneconomical with a 10% increase in fuel prices. The added sensitivity can in part be explained by the differences between the energy markets (Streckiene et al. in Germany and Fragaki et al. in the UK). For example, Fragaki et al. used a two-tariff electricity rate structure, while Streckiene et al. used an electricity spot market. However, Streckiene et al. did point out that as long as electricity prices and natural gas prices move in the same direction, then the negative impact on the economic analysis is limited. Adding TES gives the operator more market opportunities and more security because fluctuations in heat demand can be dealt with more easily, but these benefits come with additional operating risks of price sensitivity.

Pagliarini and Rainieri (2010) modeled a CHP-TES system for the University of Parma Campus in Parma, Italy. In their analysis they identified a range for the optimal TES size and found that by including a TES tank in that range the annual income increased by 48% and the overall simple payback period of the system was reduced from 4.4 to 3.5 years.

Rolfsman (2004) focused on the optimal operation of CHP-TES systems in a district heating network. Like Lin and Yi (2000), he included not just hot water TES, but also passive TES from raising building temperatures in the heating district by 1–2°C. He found that proper operation of the TES was able to keep the most expensive equipment from coming online in order to meet short spikes in heat demand. He also showed that optimal operation allowed the CHP units to work at full capacity when electricity prices are high, storing the excess heat in the TES units. The TES would then be discharged at night when it was no longer cost effective to produce electricity.

The optimal TES capacity in a district heating network is a function of the CHP system selected. For example, Lund and Andersen (2005) demonstrated that as the engine or turbine size increased (e.g., from 2 MWe to 4 MWe), the optimal size of the TES also increased. This can also be seen in the work done by Verda and Colella (2011). They found that including a second CHP system increased optimal TES size (see Figure 5). However, Fragaki et al. (2008) found that if multiple small engines or turbines were selected (e.g., two 2 MWe versus one 4 MWe) then the optimal TES size decreased because during low heat demand and low electricity prices only one engine or turbine needed to run.

The work by Urbaneck et al. (2006, 2009a,b) is interesting in that it focuses on a strictly cooling network, and that it includes CHP capacity fired by brown coal instead of natural gas. They emphasize that the optimal CHP-TES solution for one system cannot be transferred to another system without adaptation.

Bruno et al. (2010) demonstrated why ice TES is rare compared to chilled water in district energy systems. In performing their optimization of a CHP system with ice storage they found that the optimal TES size was zero while the optimal chilled-water TES size was 47.4 MWh. They suggested that ice TES is only suitable for CHP-TES district energy applications where there are significant space limitations.

As an interesting side note, the idea of extending a CHP's district heating network to outlying residences using mobile-TES has been examined by Wang et al. (2010a). They

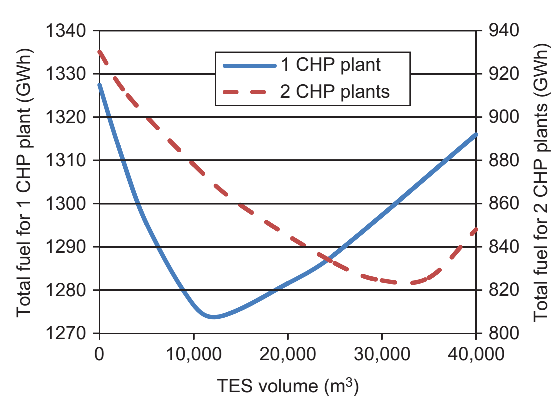


**Figure 5** Fuel requirements for 1 and 2 CHP plants versus TES volume. Note that the optimum value increases as a second CHP plant is added (Verda and Colella 2011).

considered four different options for removing heat (either via steam or hot water) from the CHP plant in order to charge the mobile-TES for distribution.

**4.5.2. Building heating and cooling** For actively cooling buildings in CHP-TES systems, chilled water and ice are the most common forms of TES, although phase change materials (PCMs) embedded into buildings to increase thermal mass have also been explored (Alanne and Paatero 2008, Domínguez et al. 2010). Except for the rare case of aquifer and borehole TES (Gaine and Duffy 2010), heating buildings in CHP-TES systems uses hot water tanks.

In the case of meeting building cooling loads, one of the major benefits of coupling TES with CHP is that it allows the equipment to be downsized. Air conditioning equipment is sized based on peak cooling demand requirements, so by incorporating TES, air conditioning equipment can be downsized which greatly reduces capital costs. For example, Ehyaei et al. (2010) looked at using micro gas turbines coupled with ice TES to meet the heating, cooling, and hot water needs for a 40-unit residential building in three different cities in Iran. The electricity from the CHP micro turbines was used to meet building electricity demands and to run mechanical chillers while the waste heat was used to run absorption chillers. In two of the cities, 21 micro turbines were required when no TES was used, but only 11 micro turbines were required when TES was incorporated. The reduction came because the TES could discharge to meet the peak demand, eliminating the need for peaking equipment that only ran during the hot afternoon periods. This resulted in a reduction in investment costs by 27.5% and 29.5%, respectively. In the third city, the ice TES reduced the required number of micro turbines from 75 to 40, resulting in a 14% saving in investment costs. The lower investment cost reduction for the third city was attributed to the hot and humid nature of its climate, while the other two cities were mild and semi-hot.

Similarly, Liu et al. (2004) examined a hybrid heating, ventilation, and air conditioning (HVAC) system that included a CHP unit, liquid desiccant, vapor compression and absorption chillers, gas boilers, and hot water and desiccant storage tanks for application in a 10-story building. During the summer the excess heat recharged the desiccant and ran the absorption chiller. In the winter the CHP unit provided space heating. The addition of TES lengthened the operating hours of the CHP system and significantly decreased the capacity of the auxiliary boiler and compression chiller. The system had a payback period of two years and reduced $CO_2$ emission by 40%.

Somcharoenwattana et al. (2011) performed two case studies, one of an airport and the other of a government office building, both located in Bangkok, Thailand. In the airport case study they demonstrated the importance of using high-efficiency equipment. The optimal economical solution was not to incorporate TES, but to replace the 20-year-old low-efficiency gas turbines with new, high-efficiency models. In the office building case study the CHP plant was designed to meet the cooling load and the electricity production was supplemental. Incorporating cold TES reduced the simple payback period of the CHP plant from 17.8 years to 9.2 years. The TES allowed the CHP to run more continuously, and decreased the size of needed equipment. The authors pointed out that the longer the operating hours of the CHP plant, the better the economic outlook of the CHP-TES system. A similar investigation with similar findings was reported by Ziher and Poredos (2006).

Khan et al. (2004) investigated energy conservation for the buildings of the Asian Institute of Technology in Bangkok, Thailand. They compared a CHP-only system and a CHP-TES system to a system where all electricity is purchased from the national grid. They included a thorough economic analysis, including installation and maintenance costs. The savings from incorporating the TES are shown in Table 1.

McNeill et al. (2007) found that incorporating a hybrid CHP-TES system that included desiccants for humidity control in a given building brought the same amount of savings regardless of location. They regressed the cost savings of the CHP-TES system in five different US cities and found that their regression coefficients were nearly identical. For a more standard CHP-TES system, however, Wang et al. (2011) found that climate influenced system energy usage and economic outlook [though they did use the non-standard objective function given in Eq. (2)]. They examined four building categories (hotel, office hospital, school) and five climates. In some of the cases with a high summer cooling load, the CHP-TES system used more energy than the conventional system during the summertime, though in only one case was the CHP-TES system less economical than the conventional system.

Other researchers have investigated CHP-TES systems for single-family residential buildings. Houwing et al. (2009) showed that using MPC on a single-family CHP-TES system brought 2–6% savings in operational costs versus the heat demand following control strategy. One of the primary benefits of adding TES to these small-scale CHP units was that the TES allowed the CHP unit to operate more continuously and for more hours of the year. Because of this benefit, a CHP system with an optimally sized TES reduces $CO_2$ emissions by almost three times compared to a CHP-only system (Haeseldonckx et al. 2007).

The type of TES model used in a building CHP-TES simulation has been shown to affect the results. Campos Celador et al. (2011) looked at the effect of how a hot water TES tank is modeled on the overall energy and exergy efficiency of a CHP facility. Energy and exergy (the maximum useful work possible) efficiency differences between perfectly stratified and fully mixed were 2% and 0.7%, respectively. However, this small difference translated into a 12% difference in annual net savings between the two tank models.

**Table 1** Savings from including CHP and CHP-TES versus purchasing all electricity from the national grid (Khan et al. 2004).

| | Peak-demand reduction | Energy reduction | Internal rate of return (IRR) |
|---|---|---|---|
| CHP only | 13% | 16% | 21% |
| CHP with TES | 23% | 21% | 25% |

**4.5.3. Integration with renewable energies** When there is a large penetration of intermittent renewable energies such as wind and solar power in the electricity sector, there needs to be some "balancing" system that can handle the intermittency. CHP-TES is an ideal candidate for balancing intermittent renewable energy sources because CHP units are often tied to thermal loads rather than electrical loads (Andersen and Lund 2007). This allows the CHP to balance an intermittent electrical load while using the TES to meet thermal demands. The incorporation of energy storage is key to increasing the system's ability to balance renewable energies (Dell and Rand 2001, Kaldellis and Zafirakis 2007, Ibrahim et al. 2008, Taneja et al. 2010). Adding TES to CHP systems improves flexibility to maximize profit (Lai and Hui 2009).

In places such as Denmark there are large amounts of electricity production coming from both wind and CHP. Because of the large penetration of wind, electricity prices are largely a function of the amount of wind: when there is an abundance of wind power, electricity prices are lower and when there is little or no wind, electricity prices are higher. This decreases the marginal value of building additional wind turbines. However, this also allows for distributed CHP-TES systems to take a larger part in the electricity system. When there is lots of wind, CHP-TES facilities can stop producing power and meet thermal loads by discharging their TES, or in very high wind scenarios, they can even purchase cheap power for running heat pumps to meet thermal loads. During low wind scenarios, the CHP units can run at full capacity, the heat pumps can be shut off, and the thermal loads can be met by a combination of waste heat and discharging the TES. In this way TES increases the flexibility of CHP to deal with the intermittency of wind (Blarke and Lund 2008, Stadler 2008).

**4.5.4. Other investigations** Caldon et al. (2004) discussed virtual power plants, which is an aggregation of distributed CHP facilities treated as a single facility. They showed that incorporation of TES in the virtual power plants reduced operation costs. Collazos et al. (2009) showed that a model predictive controller applied to CHP-TES systems in a virtual power plant setting reduced operating costs by 13% versus using a boiler and purchasing all required electricity from the grid. Wille-Haussmann et al. (2010) demonstrated that TES gives more flexibility to a virtual power plant of five CHP units. Optimal control led to a 10% cost reduction over heat demand following CHP by allowing the CHP units to actively participate in the spot market.

Ryu et al. (2008) reported on a hybrid CHP-TES system that can be applied to military-type or disaster recovery applications where the ability to island is of high priority. The system could provide all the heating, cooling, and fresh water needs of a facility (it condenses water from the air). Ryu et al. discussed the importance of selecting the appropriate heat recovery capacity as that would strongly influence the selection of other components such as TES size and chiller capacity.

Several additional investigations on CHP have been published in the literature that include, but do not focus on, interaction with TES. They include those by Porteiro et al. 2004, Linkevics and Sauhats 2005, Lund 2005, Schulz et al. 2005, Handschin et al. 2006, Hollmann 2006, Kalina and Skorek 2006, Kuhi-Thalfeldt and Valtin 2007, 2009, Hawkes et al. 2009, Dorer and Weber 2009.

### 4.6. Implications for chemical industries

Combined heat and power systems currently produce over 25% of electrical power for chemical industries (Energy Information Administration 2006). Coupling thermal storage to CHP has been shown to increase CHP operating hours, economics, and flexibility. When proper optimization and control are applied, CHP-TES units have been shown to operate effectively in district heating/cooling scenarios, building heating and cooling situations, and areas with significant renewable energy penetration. Because chemical industries can be viewed as district heating/cooling networks and often contain buildings that are heated and cooled, the principles reviewed can be directly applied. Applications from using CHP-TES to deal with intermittent renewable energy show that CHP-TES is flexible to meet plant loads that may be intermittent or uncertain. TES augments the potential of CHP to be a cost-effective and sustainable technology for the chemical industries. This may become especially valuable in smart grid environments where pricing signals to curb electricity demand (or increase electricity production) may vary hourly. TES enables the production of CHP electricity on demand without underutilizing waste heat.

## 5. Buildings and TES (without CHP)

More work has been done concerning the control and optimization of TES in the buildings sector than for any other sector. This is only logical considering the number of large-scale buildings throughout the world. Buildings are also an enormous energy sink, as 40% of all energy in the US is consumed in buildings (Energy Information Administration 2010a,b). Due to the volume of work in this area, building energy systems coupled with TES provides insight into the benefits of proper control of TES systems. The building sector has also showcased the power of model predictive control (MPC). For that reason, MPC in buildings is given special attention to demonstrate that MPC is capable of controlling complex systems while generating cost and/or energy savings.

Thermal energy storage is primarily applied to shift electrical loads from high-cost peak times to low-cost off-peak times by shifting the building's thermal load (see Figure 6). In doing so, it provides extra degrees of freedom for sizing and operating heating and cooling equipment. For example, in traditional heating and cooling systems equipment is sized to meet the peak demand for the year. For the majority of the year the equipment is not operating at peak conditions and is therefore oversized. Adding TES reduces the peak load that a chiller or boiler must meet, thereby allowing it to operate closer to its design points where its efficiency is higher (Liu et al. 1994). Other advantages of incorporating TES include using cool nighttime air to precool building mass (given the

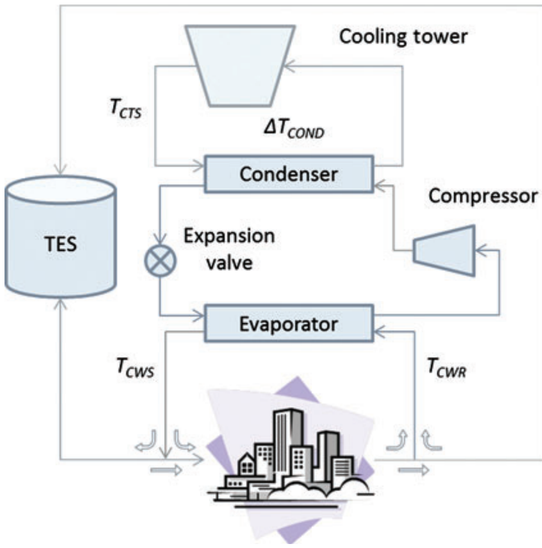


**Figure 6** Building TES cooling system. Cooling fluid from the TES flows counterclockwise during discharge and clockwise when recharging (Cole et al. 2012).

appropriate climate) and operating the system's chillers at improved ambient conditions (Braun 2003). Conditions that tend to favor the implementation of TES include high utility demand costs, high utility on-peak rates, high daily load variations, short duration loads, infrequent or cyclical loads, insufficient capacity of cooling equipment to handle peak loads, and rebates for shifting peak loads (Dincer and Rosen 2008).

The TES in buildings systems can be active or passive. Active TES is typically ice or chilled water for cooling systems and hot water for heating systems. Passive TES is most commonly sensible heat storage in the building material (i.e., the concrete, steel, etc. that make up the building), but may also include engineered phase change materials (PCMs). PCMs have been reviewed extensively (e.g., Cabeza et al. 2011), so specific information about PCMs will not be included here. Most of the literature on active TES control systems focuses on ice TES, though chilled water is very common in actual TES applications (Andrepont 2007). Modeling and control of ice TES is more challenging because of the variety of the ice-making devices and the difficulty of capturing the dynamic heat transfer characteristics as ice is formed or melted (Braun 2007). Passive TES has gained popularity in the optimal control field because, other than the controller, it can require no system changes.

### 5.1. TES control strategies

Most of the recent investigations in literature center on how the TES should be used. Determining how the TES system will be used also specifies, to some extent, the required size of the system.

Conventional TES control strategies include storage-priority, chiller-priority, and constant-proportion control (Dorgan and Elleson 1993, Henze et al. 1997, Henze 2003, Lemort 2006, Beggs 2009). Storage-priority control can be further subdivided into full-storage and demand-limiting control, though in some senses full-storage control can be seen as a special case of demand-limiting control (Dincer 2002). Results from applying these different control strategies for TES are shown in Figure 7. The only difference between the control techniques is the rate and time of the TES discharge. Chiller-priority and constant-proportion control are fairly simple to implement and may require no more than an on/off schedule. Storage-priority control is somewhat more difficult since it requires load forecasting. These control strategies are used as a metric for comparing more advanced control schemes.

Model predictive control (MPC) is a more advanced control strategy in which a model of the building and appropriate systems (e.g., chiller, ice storage tank, etc.) is generated. The controller uses the model along with weather, occupancy, and energy price predictions to determine the optimal trajectory of the planning horizon [typically 24 h, though 48 h has been used (Henze et al. 2008)], but it only takes an action for the first time step (see Figure 8). For the following time step the planning horizon is shifted forward, the optimal trajectory is recalculated, and the first action is again taken. In this way the controller is always using the model to predict behavior over the next sampling period, e.g., 24 h, but it only implements the first control action in that planning horizon. The models are often created using popular building modeling and simulation software such as EnergyPlus (U.S. Department of Energy, Washington, DC, USA) or TRNSYS (Thermal Energy System Specialists, LLC, Madison, WI, USA). These modeling tools are able to capture the dynamics of a complicated building system without spending excessive amounts of time generating a model. These models can even be coupled with tools such as MATLAB to further increase user flexibility (Nghiem and Pappas 2011).

Most researchers selected 1 h as their time step (e.g., Henze et al. 2005) but some chose smaller time steps (Lemort 2006, Braun 2007). Ma et al. (2010) showed that the choice of the time step is important. They found that by choosing too coarse a time step (they used 1 h), the MPC was not able to take full advantage of the system because the optimal time of many of the decisions occurred between the 1 h decision periods. The drawbacks of MPC include the potential high cost of generating an accurate model for the controller, unavoidable mismatch between the model and the actual environment, and the difficulty of appropriately predicting future conditions such as weather and electricity price.

Because energy systems using TES depend so heavily on environmental conditions in order to make accurate predictions and decisions about how the system operates, it is very useful to incorporate weather forecasts so that the ambient conditions and projected loads can be anticipated. Henze et al. (1997) and Henze et al. (2004a) examined various weather prediction methods for MPCs, including random walk, 30- and 60-day bin predictors, harmonic predictor, autoregressive neural network, and same-as-yesterday predictor. They found that the 30- and 60-day bin predictors were the best weather

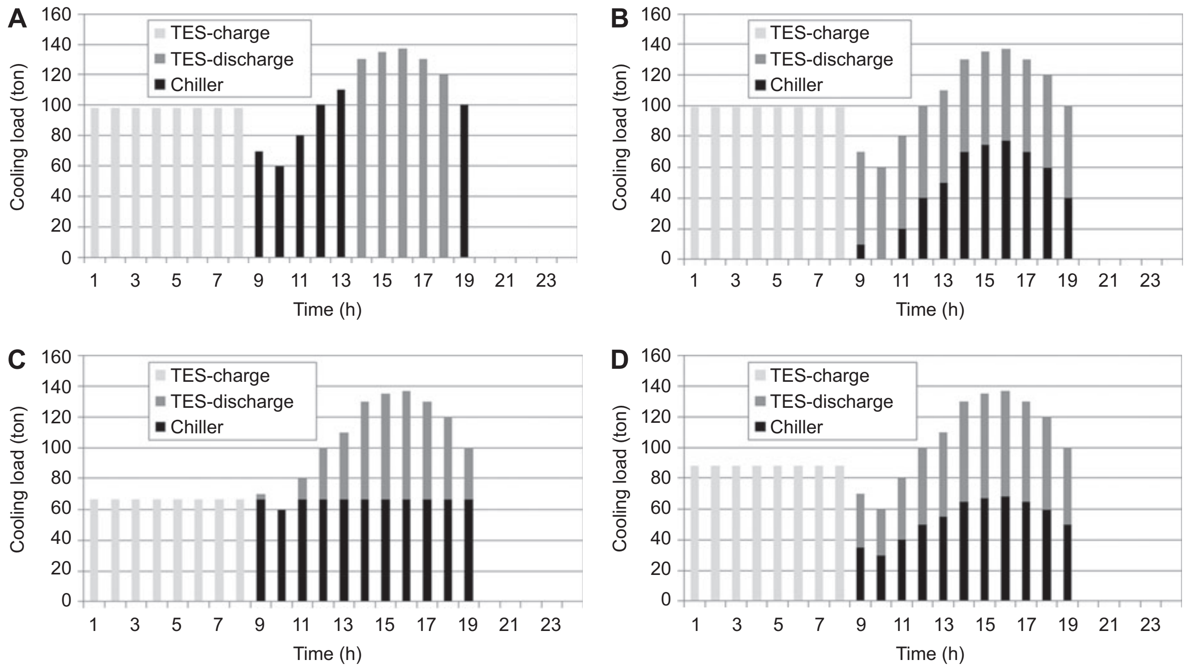


**Figure 7** Conventional active TES control strategies. Full-storage (A), demand-limiting (B), chiller-priority (C), and constant-proportion (D). Full-storage and demand limiting are both storage priority control methods.

predictors and that they led to cost savings that were only marginally worse than the perfect prediction scenarios.

Model predictive controllers have been used for passive TES (e.g., Henze et al. 2008), active TES (e.g., Ma et al. 2009), and simultaneous active and passive TES (e.g., Zhou et al. 2005a). Interest in MPC for passive TES has increased because one of the benefits of using MPC is that it can take advantage of the building's thermal mass under a variable electricity rate structure (Cigler and Prívara 2010, Široký et al. 2011). A general solution for passive TES using MPC is shown in Figure 9. The controller takes advantage of the thermal mass by precooling the building before the occupancy period begins and then gradually increases the room temperature set points during times when electricity is most expensive to allow the building mass to absorb the heat. Use of PCMs with MPC can further increase the potential of passive TES since temperature levels could be kept perpetually within the comfort range. Use of MPC with passive TES does not guarantee savings, however. Oldewurtel et al. (2010) found that in some cases a variable rate structure under optimal MPC can still increase overall energy costs versus an average, flat-rate structure because some loads such as lighting cannot be shifted to off-peak hours.

Zhou et al. (2005b) developed an MPC for an active chilled water TES system. The MPC operated differently than typical MPCs in that instead of changing equipment set points it functioned more as an equipment scheduler. The MPC predicted the campus load over the planning horizon and then determined the best time to discharge the TES, the number of chillers that must operate at each time step to meet the remainder of the load, and the start and stop times of each chiller.

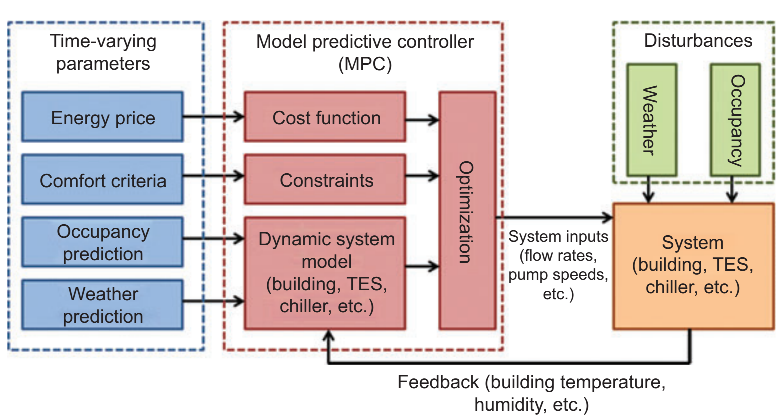


**Figure 8** Model predictive controller. Adapted from Široký et al. (2011).

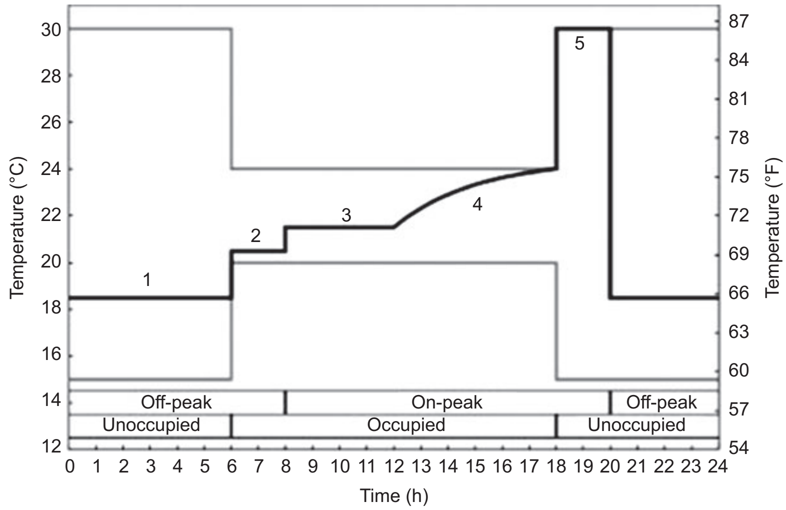


**Figure 9** Set points for optimal control of passive TES. The black line is the control path and the gray lines are upper and lower control limits (Henze et al. 2010).

Henze et al. (2004a,b) and (2005) applied MPC to a system with both active and passive TES. They solved the passive TES problem first and the active thermal storage problem second. This led to the same results as solving both problems simultaneously but took significantly less computation time and reduced the risk of landing in a local optimum. They also used the optimal solution from the previous time step as a guess value for future time steps.

Cole et al. (2012) evaluated the benefit of MPC for an active chilled water TES system using time-of-use (TOU) pricing. They found that demand charges cause the optimal cost scenario to be far different from the optimal energy reduction scenario. Their results are summarized in Table 2. Additionally, they found that 75% of the energy savings using MPC occurred during winter months, but 63% of the cost savings from MPC occurred during the summer months.

Liu and Henze (2004) analyzed the effects of mismatch between a model and an actual system when using an MPC. Incorrectly modeled building construction characteristics negatively affected the MPC's ability to fully utilize passive TES. Zone temperature set points and TES performance were strongly affected if the model contained improper internal heat gains, especially when those heat gains were under-estimated. Relative efficiencies between chillers were also quite important as they determined the order in which chillers were put on-line.

By using a fractional factorial analysis Cheng et al. (2008) found that the four factors that most influence the effectiveness and cost using passive TES with MPC were utility rate structure, internal load levels, building mass level, and equipment efficiency. In a follow-up study, Henze et al. (2010) performed a full factorial analysis on the four parameters found by Cheng et al. They considered four cities, each with its actual rate structure. They found that cost savings from passive TES were limited by the available storage capacity and that more savings could generally be achieved when the system has lower efficiency equipment because more energy usage can be shifted from on-peak to off-peak. Control strategies were simplified by applying the average of the four optimization variables, and nearly all buildings achieved equal savings as using the MPC. Savings from passive TES were most sensitive to utility rates (which was also demonstrated by Braun 2003), followed by building mass and then internal heat gains. Relative savings due to passive TES were fairly insensitive to climate. Incorporation of PCMs may change the impact of climate, though. Corgnati et al. (2009) found that the influence of PCMs was very climate dependent, but that using building thermal mass provided benefit regardless of climate.

Seo and Krarti (2007) considered the influence of building shape on TES MPC operation. They found that it had a small impact on TES performance (<5% difference in savings potential for a square building versus rectangular building). They also found that optimal control led to 15% higher savings than chiller priority.

Other controllers such as learning controllers (Liu and Henze 2007), fuzzy logic controllers (Yu and Dexter 2010),

**Table 2** Operating cost effects of a TES system using MPC to minimize cost or energy usage (Cole et al. 2012).

| System type | Objective function | Annual operating cost | Annual energy usage (MWh) |
|---|---|---|---|
| No thermal storage | – | $222,500 | 2489 |
| Thermal storage (no MPC) | – | $147,000 (-34%) | 2495 (+0.2%) |
| Thermal storage (with MPC) | Minimize operating cost | $128,700 (-42%) | 2443 (-1.8%) |
| Thermal storage (with MPC) | Minimize energy usage | $156,400 (-30%) | 2391 (-3.9%) |

heuristic controllers (Braun 2007), and weight priority method controllers (Dasi et al. 2008) have also been used for buildings that include TES with varying levels of success. However, we believe that MPC is the most versatile control type for the operation of TES.

### 5.2. Implications for chemical industries

TES and MPC have only been examined together in building heating and cooling environments, demonstrating the potential of model-based predictive controllers in TES systems. TES in buildings brings many benefits, such as reducing cycling or the size of heating and cooling equipment, but TES with MPC amplifies the benefits of TES, including enhanced economics and flexibility. TES in building systems has also shown how advanced control can take advantage of the utility rate structures to bring significant cost savings. Deployment of TES in the chemical industries would be similarly benefited if advanced controls such as MPC are applied (Henze et al. 2009).

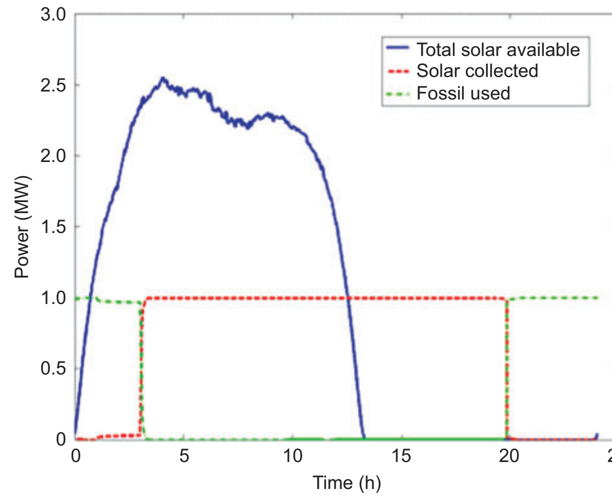


**Figure 10** Simulation results which show that despite fluctuations in available solar power, a system with TES can still produce power at a constant rate, even beyond daylight hours (Powell and Edgar 2012).

## 6. Solar thermal and TES systems

Because nearly all sources of energy ultimately come from the sun, much work has gone into developing effective methods to harness this energy. One promising technology, solar thermal energy, converts the sun's light into heat. This heat can be used directly or can further be converted to mechanical or electrical energy. TES is a natural fit for solar thermal processes, giving solar thermal technologies inexpensive storage. This is a competitive advantage that concentrating solar power (CSP) has over photovoltaic (PV) systems, which rely on electrical energy storage, typically batteries, which can be extremely expensive and often cost prohibitive.

Solar thermal energy technologies may play a role in the chemical industry, as chemical plants seek to become more reliant on renewable energy. Solar thermal chemical reactors have been researched for thermal dissociation of ZnO (Müller et al. 2006, 2008) and for thermal hydrogen production from methane (Rodat et al. 2009), to name just two applications. For reliable integration of solar thermal energy into a chemical plant, TES would certainly play a role in helping to overcome the intermittency of solar radiation and in extending operating hours into the evening after the sun has set. Some of the lessons learned in studying the dynamics of TES with solar thermal processes are illustrated here.

### 6.1. High temperature applications of TES for power generation

TES can be a very effective tool for taking advantage of renewable energy resources, particularly those that are intermittent in nature. Because energy storage can act as a buffer between the supply and demand sides of energy systems, it can effectively convert an intermittent energy source into one that can be dispatched according to demand, as Figure 10 illustrates (Powell and Edgar 2012). Thus, TES can become a key enabling technology for many solar thermal energy applications.

TES has become a key research area for improving the dispatchability (the ability to dispatch power on demand) of CSP. Unlike PV systems, which convert sunlight directly to electrical current, CSP systems concentrate sunlight to heat a fluid (see Figure 11). This heat is then used to generate steam, which is then used in a conventional power cycle, typically the Rankine Cycle.

The simplicity of thermal storage makes it an ideal match for solar thermal energy, as it provides a cost-effective solution to the problem of the irregularity of available sunlight. Because high temperature TES is such a promising technology, this topic has received attention in research of late. The vast majority of the research being done in high temperature thermal storage (>100°C) for power generation is focused on developing concepts and materials that are viable candidates for CSP applications. Gil et al. (2010) have chronicled the most recent advances in these areas and provide an excellent overview on high temperature TES technology itself. High temperature TES may use a number of materials and configurations. Sensible heat storage materials store heat by changing

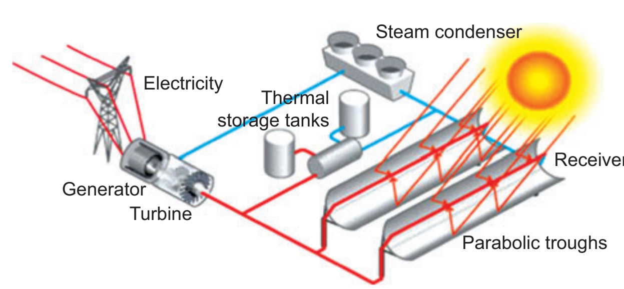


**Figure 11** A diagram of a CSP system showing the parabolic trough solar collectors, TES tanks, and power generation equipment (Department of Energy 2012).

the temperature of a material. Sensible storage systems have been developed for solid, liquid, and gas phase media. Examples include: liquid, molten salt storage (Herrmann et al. 2004); gas, direct steam storage (Steinmann and Eck 2006); solid, concrete TES (Laing et al. 2006); and combined fluid and solid, pebble bed TES (Mawire et al. 2009). Latent heat storage systems, which store heat by changing the phase of a medium, have also found use (Sharma et al. 2009).

However, despite the research and development interest in high temperature TES, there are few instances of successful applications on a large scale (Medrano et al. 2010). Because of this, the study of concentrated solar power TES systems from a dynamic systems perspective is a relatively unexplored field. However, the National Renewable Energy Laboratory (NREL) has developed a publicly available software package called the System Advisor Model (SAM, sam.nrel.gov), which performs simulations of solar thermal power plants using TRYNSYS (transient system simulation tool). This tool performs simulations of solar power facilities with TES for a given location in order to help estimate the economics of a project. This tool is valuable for estimating NPV, ROI, and payback period for solar projects with or without TES.

In order to take full advantage of a CSP with TES system, the complete system must be well understood. Because the storage is so highly integrated into the system, it is important to use a systems-level model, so that the interactions of the storage with all other components of the system can be well understood. Llorente García et al. (2011) developed such a model in order to assist with technical and economic evaluations. In this work, a detailed dynamic model of a parabolic trough CSP plant was developed and compared to operating data of a plant in Spain. The results compare well against the plant data, but the model is mainly designed to extrapolate for use in designing other plants. Dynamic models such as these can be good tools for plant design so that the expected power output can be well understood and so that the storage can be effectively utilized. A dynamic model will also greatly aid in analysis of the control system to implement in the plant. Adinberg (2011) used a plant model of a solar thermal system with TES and fossil energy hybridization to explore the solar fraction (fraction of energy from the sun provided to the power cycle) achievable with different sizes of TES. He concluded that, in order for a plant to be operated on 100% solar energy (solar fraction of 1), the system would need nearly 1000 h of full-load energy storage. Realistically, based on current technology, he concluded that for a more technically and economically feasible storage capacity of 10–14 full-load hours of storage, a plant could achieve a solar fraction between 0.4 and 0.5.

When dynamic control and optimization are taken into account, plant performance can be enhanced. Because of the sporadic nature of available solar radiation and varying utility rates, forecasting becomes an important element to improving the dynamic operation of the plant. Wittmann et al. (2011) proposed a price-driven strategy, where the forecasted electric prices for a day-ahead market were taken into account. The problem explored means to use the TES system for maximum benefit of the plant. They laid a framework for how to solve this complex optimization problem using dynamic programming, although other optimization methods such as nonlinear programming (NLP) could also be used.

Research with emphasis on the TES system for CSP plants is still a developing field. Control of concentrated solar power plants themselves has received much more research attention. These systems depend completely on solar radiation and solar radiation itself is such a widely varying disturbance variable. This makes for a very interesting and important control problem. The control problem that has been the most widely explored is that of maintaining a desired outlet temperature from the solar collector field. This problem has been addressed using many basic control methods. Generally, PID control alone is not sufficient for these types of problems, due to the large disturbances, wide range of operating conditions, and high nonlinearities of the plants. Controllers often include a feedforward term to give the controller a predictive element. These control schemes take advantage of measured disturbances, particularly solar radiation, so that the controller can be proactive, rather than relying on feedback only (Camacho et al. 2007).

In addition to basic control approaches to temperature control in CSP plants, many advanced control techniques have been applied. Stuetzle et al. (2004) developed a linear model predictive controller which used real-time measurements of solar radiation, wind speed, and ambient temperature as feedforwards in order to control outlet temperature of the solar collector field. This controller and the modeled plant to which it was applied were based on the 30 MWe Solar Energy Generating Systems (SEGS) VI plant in the Mojave Desert. Many adaptive controllers have also been applied to this control problem. These controllers account for changing plant dynamics by changing the tuning parameters of the controller, based on the plant's current operating point (Camacho et al. 1994, Coito et al. 1997). Other model-based control methods such as internal model control (Farkas and Vajk 2005) and nonlinear MPC (Pickhardt and Silva 1998) have also been developed. Fuzzy logic controllers (Luk et al. 1999) have also been used. These types of controllers use heuristic fuzzy rule bases to make decisions about the plant, based on feedforward and feedback measurements. Several other control techniques such as robust control (Cirre et al. 2007), gain scheduling control (Berenguel et al. 1996), and neural network methods (Arahal et al. 1998) have been applied to this problem. Camacho et al. (2007) covered each of these methods and others in greater depth and detail in their review paper.

### 6.2. Low temperature solar TES applications

Low temperature (<100°C) solar thermal applications are more widespread and have been around for much longer than high temperature TES in the CSP industry. This is largely because low temperature applications do not require expensive concentration equipment and can be installed on much smaller scales. Solar thermal technology has been applied to water heating, space heating, cooking, drying processes, heat collection and storage in ponds (solar ponds), air conditioning, etc. (Thirugnanasambandam et al. 2010), many of which applications can benefit from thermal energy storage.

In colder climates, solar thermal energy for space heating can greatly reduce the electric or fuel bill for residential and commercial applications. Because space heating needs are typically greater at night, when temperatures are lower, TES is required to shift the heat available during daytime hours to nighttime hours. Dynamic modeling, control, and optimization of these processes can greatly benefit performance. LeBreux et al. (2009) developed a controller for a hybrid TES system developed by Ait Hammou and Lacroix (2006) that is used to store collected solar energy, but can also be heated electrically to take advantage of off-peak electrical rates. Their controller uses weather forecasts and fuzzy logic to predict and make control decisions based on those predictions.

For solar cooking applications, Mawire and McPherson (2008) used a feedforward internal model control (IMC) structure, which uses energy input measurements to make anticipatory control moves to regulate the charging temperature of the TES system. In this strategy, a control system uses a model of the system to anticipate the effect control moves will have on the system's outputs. Mawire et al. (2009) also used this system to develop a dynamic model to simulate the discharge process of the TES system.

Exergy is frequently used in analysis of thermal storage systems and can be a valuable tool for optimizing system performance. Aghbalou et al. (2006) used exergy maximization as an objective for optimizing the performance of a solar collector and TES system.

Solar energy is an abundant energy resource and many methods have been developed to harness it. TES, combined with proper control and optimization methods, is required, however, to make the sun's energy beneficial to man. Many techniques for control and optimization of solar thermal processes have been undertaken, but this is a field that will receive considerably more attention as solar thermal technologies become more prevalent.

### 6.3. Implications for the chemical industry

With growing energy concerns facing the chemical industry, solar thermal energy may become increasingly important in the future. The sporadic nature of sunlight, however, makes it difficult to integrate solar energy as reliably as is needed for chemical processes. TES will undoubtedly be a key enabling technology to reliably incorporate solar thermal energy into the chemical industry by converting an intermittent energy source into a constant flow of energy. Process control and optimization will also play a vital role in taking maximum advantage of the resource of solar thermal power, leveraging TES technologies for optimal system performance.

## 7. Conclusions

There are many benefits and challenges to integration of TES in an energy system. Adding TES to a CHP system can improve overall system efficiency and economics, and provide some degree of independence from an external utility. TES used in building heating and cooling systems can shift peak loads and reduce the size and cost of peaking equipment or peaking energy. TES allows users to take advantage of time-of-use rates, operating equipment during times of lowest cost. Buildings with TES demonstrate that MPC is a viable control strategy to manage complicated systems in a variety of utility rate structures and that MPC amplifies the cost-effectiveness of TES systems. TES in solar thermal systems transforms intermittent energy sources into constant supply sources, reducing the need for auxiliary backup equipment, providing greater reliability, and reducing uncertainty.

In summary, we conclude that when TES is properly designed and controlled it can:

- Increase system flexibility
- Improve system efficiency
- Reduce energy consumption
- Reduce equipment costs
- Increase independence from utilities
- Reduce emissions
- Manage intermittency from an energy source or sink

Because chemical processes are often heavily integrated with significant thermal and electrical loads, we believe that TES, especially when coupled with CHP, can be applied to improve the flexibility and efficiency of chemical processes. In order to take full advantage of TES, optimization in design and control (such as MPC) is necessary.

The flexibility offered by TES is likely to become more important, especially with the advent of the smart grid and the increase in intermittent renewable energy resources. Implementation of TES may allow chemical processes to increase the amount of on-site renewable energies. As smart grid technologies are deployed, chemical plants can use TES to improve their utility economics by enhancing their interactions with the grid as they buy and sell power (or simply curb power use) at optimal times.

Because TES can reduce required equipment sizes and increase system efficiencies, it can be used to improve the economics of chemical processes. TES also reduces equipment cycling, which lengthens equipment life and decreases maintenance costs.

Based on the literature reviewed, we recommend the following for future research directions:

- The development of new materials will continue to improve flexibility and efficiency of TES systems, thus giving controllers more opportunity to generate both energy and cost savings. For example, the development of a cost-effective PCM that changes temperature at ~4°C can reduce the TES size to close to that of ice TES while at the same time reducing the compressor lift of the chiller that must charge the TES (compared to ice storage).
- Energy systems are likely to become increasingly complicated and integrated, and controlling those systems will only be possible through advanced control. The integrated systems will leverage the benefits of each of the components of the system, resulting in a more efficient and flexible system. However, models may grow sufficiently complicated

that the control cannot function optimally. Model reduction techniques and improved algorithms (especially mixed-integer algorithms) will need to be developed to address these issues.

- Increases in the amount of intermittent renewable energy sources will create a greater demand for storage. Integrating energy storage systems (e.g., TES, batteries, flywheels, etc.) may generate new opportunities to deal with these intermittencies. Research and development of new hybrid systems is likely to raise overall system efficiency and effectiveness.
- As advanced control techniques such as MPC are developed, model mismatch may become a bottleneck for improvements. Model mismatch can be reduced by improving prediction capabilities of disturbance variables, by developing dynamic models of TES-related equipment than can be packaged into commercial or open source software, and by developing adaptive abilities into the controller so that it can adjust to changing process conditions.
- Using solutions to dynamic optimization problems, real-time implementation into actual systems must be investigated. Particularly because of the stochastic nature of such problems, only the most up-to-date forecasts and plant measurements must be used each time the optimizer solves. Efficient and accurate methods to handle the stochastic nature of such problems must also be explored.
- Interaction between TES and intelligent systems such as the smart grid will become more beneficial and efficient as more companies develop products that can take advantage of intelligent storage. However, for that to be possible, interoperability and communication standards must be developed and implemented (e.g., Ghatikar and Bienert 2011).

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Received November 30, 2011; accepted February 21, 2012

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