A method to determine the optimal tank size for a chilled water storage system under a time-of-use electricity rate structure

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ABSTRACT

In the downtown area of Austin, it is planned to build a new naturally stratified chilled water storage tank and share it among four separated chilled water plants. An underground piping system is to be established to connect these four plants together. This paper presents the method of determining the optimal tank size as well as corresponding optimal operating strategies for this project. Based on the analysis of the historical log data, utility rate structures, and equipment information, the baseline profiles of electricity fed to buildings, plant cooling load, and utility billing cost for each plant are generated. A simplified TES plus four plants model is built based on some assumptions. The results show that a 3.5 million gallon tank has the shortest payback time and the projected total capital cost is within the budget. The annual billing cost savings are $907,231 and the simple payback time is 12.5 years.

INTRODUCTION

Thermal Energy Storage (TES) technology is often used to reduce the operating costs by shifting cooling production from higher cost periods to low cost periods. The electricity energy savings can also be achived by shifting the cooling load from less efficient chillers (CHLR) to more efficient chillers (such as new electric centrifugal chillers) or loading chillers at the optimal Part Load Ratio (PLA). In an energy retrofit project, a chilled water (ChW) storage system is ofen prefered since existing equipment can be kept and the least system changes to the original system configuration have to be made. In the preliminary study phase, the available information is limited, but the derterminzation of an optimal tank size as well as the energy and cost savings estimation will be critical for decision-making. Although the concept is very simple, the various operation modes together with complicated rate structures enhance the difficulties and complexities of determining the tank size and the optimal operating strategies. In this phase, hand calculation or typical day simulations are often used but its accuracy and reliability is a question. Therefore, a simple method is needed to help designers select an optimal tank size, determine optimal operating strategies, and estimate the savings potential based on limited information and assumptions. It should be performed within a reasonable time, while yield accurate and reliable results.

An in-depth literature search and study shows that the studies on ChW storage systems are mainly concentrated on field experiment testing of the tank performance. Tran et al. (1989) tested six chilled water storage systems and found that well-designed storage tanks had a Figure-of-Merit (FOM) of 90% or higher for daily complete charge and discharge cycles and between 80% and 90% for partial charge and discharge cycles. Bahnfleth and Musser (1998) found that the lost capacity was roughly 2% of the theoretical capacity available when a minimum outlet temperature limit was applied while as much as 6% could be lost for discharge processes performed at the same flow rate for typical limiting temperatures. Discharge cycle lost capacity was significantly decreased by reducing the inlet flow rate. In a dynamic mode of operation, the effects of mixing overtook the influence of other parameters but the effect of wall materials could not be neglected when the tank was in an idle status (Nelson et al. 1999b). Caldwell and Bahnfleth (1998) found that mixing was localized near the inlet diffuser and directly related to flow rate. Nelson et al. (1999a) proposed the definition of the mixing coefficient, which was expressed as a function of Reynolds number (Re) and Richardson number (Ri).

Other researchers built dynamic or static simulation models to study the thermal performance of a stratified ChW storage tank. Gretarsson et al. (1994) derived a fundamental energy balance model based on a one-dimensional plug-type flow approach. Studies showed that the thermocline thickness could be 3% to 7% of the water height. Homan et al. (1996) grouped the capacity loss into heat transfer through the tank walls, conduction across the thermocline, and the flow dynamics of the charge and discharge process and found that the flow dynamics were generally orders of magnitude more important than the other factors. Published data showed current storage tanks generally operated at efficiencies of 50% to 80%.

These studies indicate that considerable capacity loss may occur when a minimum outlet temperature limit is applied, especially during a discharge cycle at higher flow rate. The tank discharge rate should be controlled to minimize the mixing effect near the inlet diffuser. These findings could place some constraints on the operations of the TES system and also provide insights to simply quantify the tank performance.

Henze et al. (2008) described the investigation of the economic and qualitative benefits of adding a chilled water thermal energy storage system to a group of large buildings in the pharmaceutical industry in Southern Germany. It is found that the adoption of a chilled water thermal energy storage system is expected to provide economic benefits as measured in energy cost savings, as well as qualitative merits such as the avoidance of numerous safety measures necessary for a chilled water plant without storage (e.g., always operating at least two chillers), and a cost effective addition of supplemental chilled water plant cooling capacity. Moreover, the overall system reliability and availability will be significantly improved through the addition of a thermal energy storage system. The near-optimal heuristics suitable for implementation in the actual pharmaceutical buildings is an on-going task. Zhou et al. (2005) developed a chiller start-stop optimization program and implemented it into the energy management and control system to determine the number of chillers that need to be brought on line and the start and stop times for each chiller every day, based on the prediction ofthe campus cooling load within the next 24 hours. Wei et al. (2000) developed control strategies for both on-peak and off-peak months to minimize demand charges for a 7000 ton-hour (24,618 kW-hour) chilled water storage system serving a hospital. By optimizing the operation of the building air handling units, chilled water pumps, chiller plant and the thermal storage system, the storage tank is better charged while chiller run time is reduced. Both on-peak and off-peak electrical demands are expected to be reduced significantly. All these studies are on a case by case base and the effect of loop chilled water supply and return temperature degradation is not considered. However, in practice, low delta-T is common for an aged chiller plant, and it can reduce the tank capacity directly. The tank state and state change are described with ton and ton-hour, respectively, which will lead to inconsistency for a chilled water storage tank when the loop delta-T fluctuates.

The electricity rate is the main driving force and the economic incentive for the application of a TES system. There are various kinds of rate structures but a Time-of-Use (TOU) rate structure is most popular for a TES system. A TOU rate defines the cost of energy during specific times of the day and encourages customers to defer energy use until costs are lower. It is fixed in advance usually at the time of signing the contract, and is not subject to variations during the contracted period. Sometimes, the calculation of monthly billed demand can be very complicated if a ratchet is defined (Wei et al. 2002).

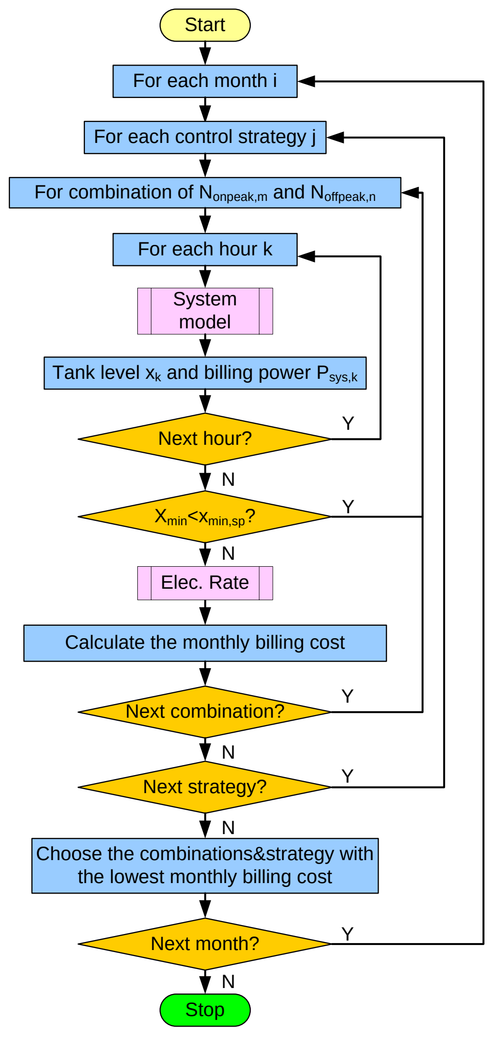

Figure 1. Flow chart for searching the near-optimal control strategy for each month

This paper discusses a simple method to select an optimal tank size under a typical TOU rate structure for a retrofit project. Hourly simulations are performed month by month to determine the corresponding optimal operating strategies. The effects of chiller performance, loop ChW delta-T, tank performance, and cooling load profile are all considered.

METHOD

This method is based on a direct search of all possilbe operating strategies, which consist of control strategy type and the maximum number of chillers running during the off-peak and on-peak periods. For each cycle, normally 24 hours, it is divided into off-peak peirod and on-peak period. **Figure 1** shows the flow chart of the search procedure. Within the search loop, all possilbe combinations are explored. The hourly tank water level and system total power are simulated with a model called system model. A minimum tank level setpoint is used to filter the combinations that lead to premature depletion. For all acceptable combinations, an electricity rate model is used to calculate the monthly billing cost. The scenario with the lowest monthly billing cost will be chosen as the optimal operating strategy for the current month.

The maximal numbers of chillers that can be staged on should be no less than zero and no higher than the number of installed chillers in the plant. The limitation on the number of chillers running is a kind of demand limiting because, for a multi-chiller plant, the ChW-related power is directly proportional to the number of chillers running. Each control strategy consists of a series of control logic, which is used to calculate the plant total ChW flow rate and the number of chillers staged on for each time step. The control strategies used include three conventional strategies, which are elaborated in other sections. In addition, the scenario without TES is also simulated as a baseline when calculating the energy and cost savings.

Following this procedure, it is possible to perform multiple simulations under scenarios with various inputs, such as high or low cooling load, good or poor tank performance, constant or variable loop delta-T, ect. Comparison of the results can provide an insight into the sensitivity of the estimated cost savings or simple payback time on these parameters.

System Model

The flow chart of a system model is shown in **Figure 2**. It is used to calculate the hourly tank water level and system total power. This model includes three sub-models and each of them will be introduced in the following sections. The advantage of such a system model is that each sub-model is independent and its function is explicitly specified. It also clearly describes the relationships among plant, loop, and TES tank. For different applications, the user may replace them with self-built sub-models or make minor changes on the original ones. In addition, the user can design a new control strategy to maximize the savings based on case by case considerations.

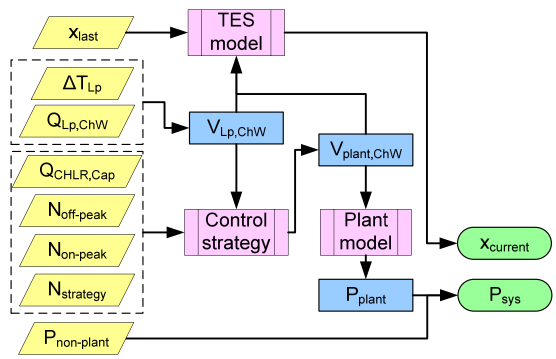

Figure 2. Flow chart of system total power simulation

TES Model

In this study, the tank ChW volume ratio and the tank charging or discharging flow rate are utilized to describe the tank state and inventory change rate. The tank inventory x is explained as the ChW volume ratio in the tank. The state of a full tank is unity and of an empty one is zero. The primary controlled variable $V_{Tank,ChW}$ in gallons per minute (GPM) is defined as the rate change of the tank inventory x_k.

$$x = \frac{U_{Tank,ChW}}{U_{Tank}} \quad (1)$$

$$V_{Tank,ChW} = \phi \frac{dU_{Tank,ChW}}{dt} = \phi \left(V_{Plant,ChW} - V_{Lp,ChW} \right) \quad (2)$$

$$x_{k+1} = x_k + \phi (V_{Plant,ChW,k} - V_{Lp,ChW,k}) \frac{\Delta t}{U_{Tank}} \quad (3)$$

subject to the constraints

$$x_{min} \le x_k \le x_{max}$$
$$0 \le V_{Plant,ChW,k} \le V_{Plant,ChW,\max}$$
$$V_{Tank,ChW,\min} \le V_{Tank,ChW,k} \le V_{Tank,ChW,\max}$$

The Figure-of-Merit (ϕ) is 0.85~0.98 during charging and close to unity during discharging or idle. The terms x_{min} and x_{max} are the upper and lower limits of the tank inventory and are subject to the operating strategy selected. Higher values of x_{min} and

x_{max} mean a lower risk of depleting the tank prematurely but lead to higher energy losses due to heat transfer and over charging. The plant side maximum flow rate $V_{Plant,ChW,max}$ is governed by the chilled water primary pump maximum flow rate and chiller ChW flow rate upper limit, whichever is smaller. It is inadmissible if the control action $V_{Plant,ChW,k}$ leads to x_k less than zero or greater than unity. In addition, due to the limitations in the flow rate into and out of the tank to restrain mixing effects, an additional constraint is applied to the tank maximal charging ($V_{Tank,ChW,max}$) and discharging rate ($V_{Tank,ChW,min}$) based on the tank design parameters.

At a given loop cooling load and loop ChW delta-T, the loop chilled water flow demand can be calculated with the following formula:

$$V_{Lp,ChW} = \frac{24Q_{Lp,ChW}}{\Delta T_{Lp}} \quad (4)$$

As the loop side total ChW flow ($V_{Lp,ChW,k}$) is subject to the loop side demand, the tank charging or discharging flow rate is, in fact, controlled by the plant operation ($V_{Plant,ChW,k}$). The tank level change can be calculated from Equation (3). The charge and discharge cycling period is one day or 24 hours.

Plant Model

In the TES simulation, for each given plant total ChW flow rate and loop ChW delta-T, the ChW plant model will export the total plant power under the given conditions. In this study, an equipment performance-oriented plant model is proposed to calculate the plant power under predefined conditions. This model is based on a Wire-to-Water (WTW) plant efficiency concept. The plant total power can be calculated from the following formula:

$$P_{plant} = (\xi_{CT} + \xi_{CWP} + \xi_{CHLR} + \xi_{PPMP} + \xi_{SPMP}) Q_{Plant,ChW} \quad (5)$$

The WTW efficiency of each equipment, including cooling towers (CT), condensor water pumps (CWP), chillers, ChW primary pumps (PPMP) and secondary pumps (SPMP), can be estimated based on the trended data, spot test data, or equipment specifications.

Control Strategy

According to the definition of a control strategy, it is essentially a tag given to a sequence of operating modes that covers a single cycle of the cool storage system. This cycle is one day in this study. The objective is to reduce the electricity consumption while avoiding prematurely depleting the tank. The inputs of the control stragegy sub-model are the combination of control strategy type and chiller number limiting, while the output is the plant ChW total flow rate and staging of chillers. The plant ChW flow rate is limited by the chiller maximum chilled water flow rate, which is:

$$V_{Plant,ChW,max} = N_{max} \frac{24Q_{CHLR,Cap}}{\Delta T_{Lp}} \quad (6)$$

For a TOU rate, the full storage control strategy can be stated as:

$$V_{Plant,ChW} = \begin{cases} V_{Plant,ChW,max} & x \le x_{max} \quad off-peak \\ V_{Lp,ChW} & x = x_{max} \quad off-peak \\ 0 & x \ge x_{min} \quad on-peak \end{cases} \quad (7)$$

The chiller-priority control can be stated as:

$$V_{Plant,ChW} = \begin{cases} V_{Plant,ChW,max} & x \le x_{max} \quad off-peak \\ V_{Lp,ChW} & x = x_{max} \quad off-peak \\ min(V_{Plant,ChW,max}, V_{Lp,ChW}) & x \ge x_{min} \quad on-peak \end{cases} \quad (8)$$

The storage-priority control strategy can be stated as:

$$V_{Plant,ChW} = \begin{cases} V_{Plant,ChW,max} & x \le x_{max} \quad off-peak \\ V_{Lp,ChW} & x = x_{max} \quad off-peak \\ \left[\sum_{on-peak} V_{Lp,ChW,k} - U_{Tank}(x_s - x_{min}) \right] \Big/ 60t_{on-peak} & x \ge x_{min} \quad on-peak \end{cases} \quad (9)$$

Rate Structure

The electric utility rate schedule is the main driving force for TES applications. A TOU rate structure is often used for a ChW storage system. For each day, it is divided into off-peak hours and on-peak hours. The monthly cost function can be stated as:

$$C = C_{const} + R_{d,off-peak} P_{off-peak} + R_{d,on-peak} P_{on-peak} + R_{e,off-peak} E_{off-peak} + R_{e,on-peak} E_{on-peak} \quad (10)$$

For a specific control strategy, it is necessary to define an on-peak period and an off-peak period. In most cases, this definition matches the definition of on-peak and off-peak hours for energy or demand rates. For summer billing months and winter billing months, such a definition could be different when the electrical rate structure changes.

APPLICATION

Site Description

In the downtown area of Austin, the chilled water for nineteen buildings is supplied by four separated ChW plants. An energy retrofit project is proposed to erect a chilled water storage system and connect the four separated ChW plants into one ChW loop to substantially reduce the state's utility billing costs of the plants. The purpose of this study is to select an optimal tank size and determine the optimal operating strategies.

The four plants studied are CPP, SFA, REJ, and WPC. The CPP supplies steam and chilled water to fourteen buildings. Part of the electric power fed to the CPP is distributed to Buildings ARC, SHB, and JHR. The SFA plant supplies chilled water and heating hot water (HHW) to Buildings LBJ, WBT, and itself. Part of the electric power fed to the SFA plant is distributed to the Building SFA. The REJ plant services the Building REJ with ChW, HHW, and electricity. The WPC plant services the WPC building with ChW, HHW, and electricity.

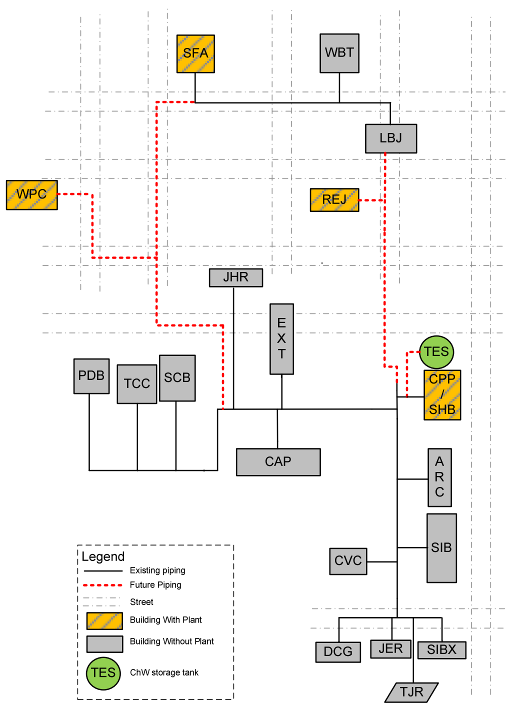

Figure 3. Schematic of ChW piping structure

Since the existing underground ChW piping diagram could not be obtained during the assessment phase, a schematic diagram of the existing ChW systems based on the walk-through is shown in **Figure 3**. The TES tank is initially planned to be in the SHB. The SFA and WPC plants tie in on the CPP loop at the JHR building so as to ease the ChW drought on the CPP west loop. The REJ plant can tie in on the CPP loop at the SHB building. The assumed new piping layout is shown with dotted lines in **Figure 3**. The goal was to connect the four plants into a loop intended to share the TES tank and take advantage of redundant cooling capacity in each plant. A ring-loop is constructed to provide a higher safety factor for system operations. The total length of the new pipes is estimated to be 3096 ft (943.7 m). The final piping arrangement will be subject to further adjustment when existing piping size, future tank location, construction cost, and other factors are considered.

The summary of the chiller information for each plant is show in

Table 1. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards, centrifugal chillers have a service life of 23 years. This means that the chillers in the CPP plant, in order of oldest to youngest, are or were due for replacement in 2005, 2013, 2017, and 2024. CH2 in the CPP plant has been replaced with a new 1450 ton (5099 kW) chiller. CH1 and CH3 in the SFA plant has been replaced with two 1550 ton (5451 kW) chillers. In the REJ plant, all of the chillers are relatively new and there is no replacement plan at present.

Table 1 Chiller information summary in four plants

Plant	Chiller	Manufacturer	Capacity	Year
CPP (SHB)	1	Trane	1470	2001
	2	Trane	1450	2009
	3	Trane	1250	1990
	4	Trane	1280	1994
SFA	1	Trane	1550	2009
	2	Trane	1470	2003
	3	Trane	1550	2009
REJ	1	Trane	555	1998
	2	Trane	555	1998
	3	Trane		
	4	Trane	70	1998
WPC	1		800	1985
	2		800	1985

The two 800 ton (2813 kW) chillers in the WPC plant are scheduled to be replaced in 4 to 5 years. However, the installation of a new TES tank could make these retrofits less urgent and the cost to replace these two chillers will be considered as a potential avoided cost in the economic analysis.

The total cooling capacity is 5450 ton (19,167 kW) for the CPP plant, 4570 ton (16,072 kW) for the SFA plant, 1180 ton (4150 kW) for the REJ plant, and 1600 (5627 kW) ton for the WPC plant. Since the CPP and SFA plants are newer than the REJ and WPC plants, they are assumed to have a higher performance. In this context, the chillers installed after 2000 are called new chillers and the chillers installed before 2000 are called old chillers.

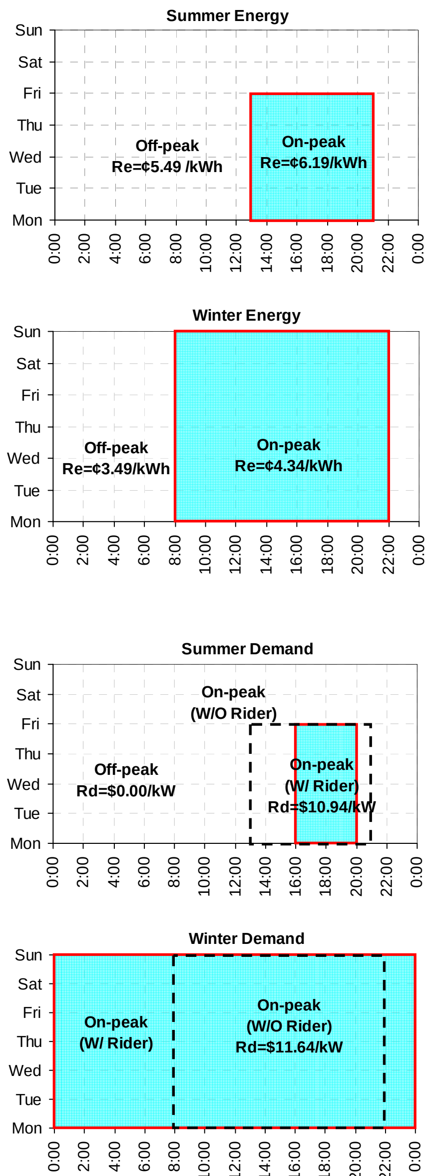

Figure 4. Electricity rate structure with and without Rider TOU

Electricity Rate Structure

Currently, the four plants are charged with three different rate structures. When a TES tank is erected and four plants are connected together with underground piping, they are all charged with the rate structure shown in **Figure 4**. A Rider clause (Rider TOU-Thermal Energy Storage) may be applicable to the four plants if the demand shifted to the off-peak period with a TES tank is no less than the lesser of 2500 kW or 20% of the customer's normal on-peak summer billed demand. The new transmission charge, beginning in 2009, will be applied to all rate structures, and the price is $0.21207 US doller ($) per monthly peak kW. The transmission demand is the highest kW in each month. According to the utility rate policy, the off-peak demand, on-peak demand, and transmission demand are all corrected to 85% power factor in the following simulations. The monthly average power factors for each plant in 2008 are used in the simulation.

According to the policy of the Rider, the summer (May 1 through October 31) demand on-peak hours are from 4:00 p.m. to 8:00 p.m., Monday through Friday (except for Memorial Day, Independence Day, and Labor Day). The remaining summer hours are considered off-peak hours (It is 1:00 pm to 9:00 pm if this Rider clause is not applied). The winter billing demand on-peak is all hours (It is 8:00 am to 10:00 pm if this Rider clause is not applied). The winter billed demand shall be the highest fifteen-minute demand recorded during the month, or 90% of the summer billed demand set in the previous summer; whichever is less (This clause does not exist if the Rider clause is not applied). The summer energy on-peak hours are from 1:00 p.m. to 9:00 p.m., Monday through Friday, and the winter energy on-peak hours are from 8:00 a.m. to 10:00 p.m., Monday through Sunday. The remaining summer hours are considered off-peak (This clause is the same as those without the Rider clause).

Baseline Development

As the cooling energy produced at each plant is not metered, the baseline cooling load profile for each plant is estimated based on the hourly electricity consumption profile for each plant. The electricity distributed from the plants to the buildings was estimated using the building electricity usage indexes and the building gross square footage. The electricity used for chilled water production is equal to the metered total electricity consumption minus the electricity distributed to the buildings. The hourly ChW load baseline profile can be obtained by dividing the electricity consumption for ChW production (kWh) with the estimated overall plant performance (kW per ton).

The following assumptions are made to develop the cooling load baseline, electricity fed to buildings, and utility billing cost baseline:

1. The selected baseline period is from January 01, 2008 to December 31, 2008.
2. The overall average performance is 1.0 kW per ton for the CPP and SFA plants and is 1.1 kW per ton for the REJ and WPC plants.
3. The four plants are charged with the original electric rate structures. The transmission charge is applied in the utility billing cost calculations.
4. In the CPP and SFA plants, the old chillers will not be staged on until the new chillers cannot meet the cooling load.
5. The TES tank is not built and there are no Continuous Commissioning® measures implemented in the CPP plant and loop.

Scenario Simulation Settings

Based on the chiller logs recorded by the plant operators and field investigations, the following are some assumptions made in the TES simulation:

1. The changes of loop side cooling load and electricity fed to buildings from the four plants due to weather adjustments and the proposed building retrofits and commissioning are not considered in the analysis.
2. The efficiency of the new chillers and old chillers is estimated to be 0.6 and 0.9 kW per ton respectively. The efficiency of cooling tower fans and ChW primary pumps is 0.1 kW per ton and the efficiency of ChW secondary pumps is 0.1 kW per ton.
3. When a TES tank is installed and new ChW piping is buried, all plants are charged under the rate structure shown in **Figure 4** with the Rider clause and the transmission charge item.
4. Three conventional control strategies (full storage, chiller priority, and storage priority) with limiting on the maximum number of chillers running during the off-peak and on-peak periods are simulated to find the optimal operation strategy for each month.
5. For each control strategy, the on-peak control period during the summer months is from 4:00pm to 8:00 pm when the demand cost is high. During the winter months, the on-peak control period is defined as 8:00 am to 10:00 pm, which matches the energy on-peak hours in the winter months.
6. The loop ChW supply and return temperature difference is 10 ºF (5.6 ºC) constant for the whole year.
7. The FOM of the storage tank is 0.98.
8. The tank water minimum level is 0.2 and the maximum level is 1.0.
9. The new chillers in the CPP plant will be staged on first, followed by the new chillers in the SFA plant. The old chillers will be staged on when all new chillers have been staged on.
10. The maximum load for each chiller is equal to its nameplate capacity.
11. The rebate from the utility company and maintenance & operation cost change are not considered in the economic analysis.

As a result, the operating strategy of the tank is to shave the on-peak demand during the summer months and is to decrease the energy consumption by reducing chiller run time during the on-peak period of the winter months. For each month, the operating strategy with the lowest monthly billing cost is selected as the optimal one.

Simulation Procedure and Results

Eight tank size scenarios are simulated: 1.0 million (M) gallon (3785 m^3), 2.0 M gallon (7571 m^3), 3.0 M gallon (11,356 m^3), 3.5 M gallon (13,249 m^3), 4.0 M gallon (15,142 m^3), 5.0 M gallon (18,927 m^3), 6.0 M gallon (22,712 m^3), and 7.0 M gallon (26,498 m^3). For each tank size scenario, the monthly savings are summed to obtain the total annual savings.

The estimation of the tank cost is based on the information provided by a TES tank manufacture. The piping cost including design, material, construction, and installation is estimated to be $8,854,560. The estimated avoided chiller cost at the WPC plant is $1,881,344. Based on all these considerations, a simple payback in years was calculated for each option.

The simulation results for eight tank size options are summarized in Table 2. As expected, a larger size tank can shift more electricity load during the on-peak period to the off-peak period and lead to a higher on-peak demand reduction and annual total billing cost savings. When the tank size is larger than 3.5 M gal (13,249 m^3), the total demand cost savings tend to approach a constant value. The summer on-peak demand reduction also remains 5036 kW. More than half of the cost savings come from demand cost reductions. The total energy reductions are over 2.0 million kWh, which is explained by cooling load shifting from low efficiency chillers to high efficiency chillers. The tank heat loss also leads to extra cooling production. A larger tank leads to a higher extra cooling production.

When the new piping cost, tank cost, and avoided chiller cost are accounted for, the simple paybacks are calculated, which are shown in Table 3. All options except for the 1.0 M gallon tank option qualify for the Rider clause. The tank size will also be limited by the available lot size and available project budget. A very large or very small tank makes the payback longer. Since the option with a 3.5 M gallon (13,249 m^3) tank has the shortest payback time and the capital cost is within the budget, it is recommended as the optimal option. The total capital cost is $13,241,232 and the annual billing cost savings are $907,231. The summer on-peak demand total reduction for four plants is 5036 kW or 45.9% of the total summer on-peak billing demand in 2008. It is noted that no rebate from the utility company is assumed. The utility will provide a rebate for TES, but the exact amount is not known at this point. The simple paybacks will be significantly less when the rebates are included.

The monthly results for a 3.5M gallon (13,249 m^3) tank option are shown in Table 4. The total electrical energy reduction is 2,377,427 kWh per year. The total billing cost savings ($907,231 per year) come from the energy cost savings ($264,109 per year) and demand cost savings ($643,121 per year). Storage priority control strategy is used during the winter months, while full-storage control strategy is preferred during the summer months. During the winter months, the maximum number of chillers on-stage during the on-peak period is limited to 2 or 3 to reduce on-peak electricity consumption. During the summer months, the maximum number of chillers staged on during the on-peak period is zero, which means no chiller is staged on and the TES tank can meet the chilled water demand during the on-peak period. The maximum number of chillers staged on during the off-peak period is 4 or 5 to fully charge the tank. This also indicates that only the new chillers in the CPP and SFA plants will be staged on, while the older ones will be on standby.

Table 2 Billing costs and energy simulation results summary

Tank (M gal)	Annual billing cost savings ($)	Annual cost savings percentage	Annual energy cost savings ($)	Annual demand cost savings ($)	Total elec. consumption reduction (kWh)	Demand reduction (kW)	Annual cooling increase (ton-hr)
1.0	$ 471,298	10.1%	$ 223,536	$ 247,762	2,863,909	2059	6,007,818
2.0	$ 627,097	13.5%	$ 240,909	$ 386,188	2,688,822	3127	6,051,099
3.0	$ 798,285	17.1%	$ 256,078	$ 542,207	2,478,769	4345	6,094,219
3.5	$ 907,231	19.5%	$ 264,109	$ 643,121	2,377,427	5036	6,114,129
4.0	$ 912,437	19.6%	$ 269,598	$ 642,838	2,326,156	5036	6,123,930
5.0	$ 922,487	19.8%	$ 280,153	$ 642,335	2,211,959	5036	6,144,385
6.0	$ 932,876	20.0%	$ 290,422	$ 642,454	2,095,404	5036	6,164,696
7.0	$ 940,319	20.2%	$ 297,746	$ 642,573	2,008,835	5036	6,180,300

Table 3 Simulation results of eight tank size options

Tank size (Million gal)	Annual billing cost savings ($/year)	Avoided CHLR cost in WPC ($)	Tank cost ($)	Piping cost ($)	Total capital cost ($)	Simple payback (years)	Qualified for Rider TOU-TES?
1.0	$ 471,298	$1,881,344	1,841,448	8,854,560	10,695,982	18.7	N
2.0	$ 627,097	$1,881,344	2,859,573	8,854,560	11,714,082	15.7	Y
3.0	$ 798,285	$1,881,344	3,877,698	8,854,560	12,732,182	13.6	Y
3.5	$ 907,231	$1,881,344	4,386,760	8,854,560	13,241,232	12.5	Y
4.0	$ 912,437	$1,881,344	4,895,823	8,854,560	13,750,282	13.0	Y
5.0	$ 922,487	$1,881,344	5,913,948	8,854,560	14,768,382	14.0	Y
6.0	$ 932,876	$1,881,344	6,932,073	8,854,560	15,786,482	14.9	Y
7.0	$ 940,319	$1,881,344	7,950,198	8,854,560	16,804,582	15.9	Y

Table 4 Monthly simulation results for a 3.5 M gallon tank

Month	Elec. Energy savings (kWh)	Energy cost savings ($)	Demand cost savings ($)	Control strategy	off-peak num	on-peak num
1	172,807	$ 24,619	$ 47,278	Storage-priority	4	3
2	155,522	$ 23,248	$ 48,383	Storage-priority	5	2
3	167,428	$ 24,631	$ 50,178	Storage-priority	4	3
4	170,318	$ 23,811	$ 51,736	Storage-priority	4	3
5	199,848	$ 18,692	$ 58,747	Full storage	5	0
6	239,460	$ 21,032	$ 60,030	Full storage	5	0
7	259,450	$ 21,919	$ 62,638	Full storage	5	0
8	258,152	$ 22,736	$ 62,176	Full storage	5	0
9	231,960	$ 19,127	$ 58,275	Full storage	5	0
10	193,506	$ 16,715	$ 50,138	Full storage	4	0
11	171,877	$ 23,764	$ 44,533	Storage-priority	4	2
12	157,098	$ 23,816	$ 49,010	Storage-priority	4	2
Total	2,377,427	$ 264,109	$ 643,121			

Table 5 Parameter range of sensitivity study

Variables	Unit	1	2	3	4	5	6	7
Tank FOM	-	1.00	0.98	0.96	0.94	0.92	0.90	0.88
ChW DT	ºF	11.5	11.0	10.5	10.0	9.5	9.0	8.5
Load Factor	-	1.08	1.04	1.00	0.96	0.92	0.88	0.84
Tank min level	-	0.35	0.30	0.25	0.20	0.15	0.10	0.05

This is only a simulation based on the information available at the present time. An in-depth engineering study is needed to determine more details when additional information and data are available, such as average plant performance, piping costs, loop load changes due to building commissioning and weather, TES storage plant placement, and other data.

Sensitivity Study

In this study, some important parameters use estimated values and are assumed constant all year around. It is necessary to test if the uncertainties of these parameters can significantly change the payback time. The selected parameters are FOM, loop ChW delta-T, cooling load factor, and tank minimal ChW water level setpoint. Seven scenarios are designed for each parameter. A 3.5 M gallon (13,249 m^3) tank is used for the sensitivity study. The annual savings and payback time are calculated for all scenarios shown in Table 5. For each parameter, the scenario shaded is the default value used in the previous simulations.

The sensitivity of the TES system simple payback to different parameters is shown in **Figure 5**. It is noted that the most sensitive parameter is load factor, while the least sensitive one is the tank minimum ChW level. Even as the tank minimum level changes from 0.35 to 0.05, the payback shortens only 0.2 years. The payback time will increase only 0.4 years even if the tank FOM drops from 1.00 to 0.88. However, if the plant load factor decreases from 1.08 to 0.84, the payback time reduces 3.1 years. As the Continuous Commissioning® is conducted on the building side, an obvious ChW consumption reduction is expected in the future and a shorter payback time will be expected, accordingly. The loop delta-T has no obvious effect on the payback until it is less than 9.5ºF (5.3 ºC) when one chiller has to be staged on during the on-peak period. This is due to a reduced tank capacity because of a lower loop ChW delta-T.

As an important factor, the summer on-peak demand reduction is also calculated for each scenario, which is shown in **Figure 6**. The effect of tank FOM, ChW delta-T, and load factor on the demand reduction is negligible. However, the demand reduction drops 692 kW if the loop delta-T is reduced to 8.5°F (4.7°C). A higher delta-T leads to a higher tank inventory and more electricity load can be shifted from the on-peak hours to the off-peak hours. Finally, the actual cooling profile is important to determine the demand. Even if the cooling load increases by 8% compared to the baseline, the on-peak demand reduction does not change due to sufficient tank capacity.

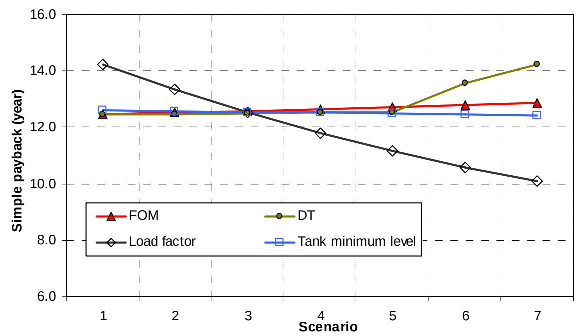

Figure 5. TES tank payback sensitivity to variants of plant parameters

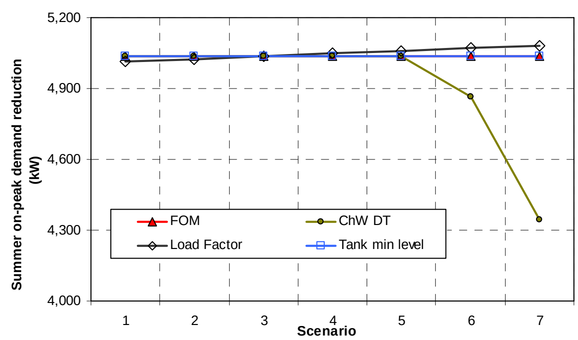

Figure 6. TES tank on-peak demand reduction sensitivity to variants of plant parameters

SUMMARY AND CONCLUSION

A chilled water storage tank is preferred for a chiller plant retrofit project to shave the on-peak demand and level out the off-peak demand so as to reduce the utility billing cost. However, it is difficult to accurately estimate the energy and cost savings potential when complicated utility rate structure, cooling load profiles, and system performance are invloved. Particularly, during the initial phase, the available information is very limited and some assumptions are needed to move forward with the preliminary study. It is important to determine the sensitivity of the savings estimation and conclusions to the variants of these assumptions.

This paper discussed a simple and general method to select an optimal tank size under a typical TOU rate structure. It is based on a new classification of operating strategies and a comprehensive search path. Each operating strategy consists of a type of control strategy and the maximum numbers of chillers on-stage during the off-peak and on-peak periods. For each month, a search is performed for all possible operating strategies, and the hourly profiles of the tank chilled water level and system total power are simulated by a system model. Following a filtering clause, an electricity rate model is run to calculate the monthly billing cost of each feasible operating strategy. The operating strategy with the lowest billing cost is selected as the optimal strategy for the current month.

In the system model, the ChW volume is used to describe the tank inventory, and the ChW flow rate is selected to quantify the inventory change. The tank operating mode is controlled by modulating the plant total ChW flow rate. At a given plant ChW flow rate and delta-T, the plant power is calculated with a wire-to-water efficiency in kW per ton for each type of equipment. The loop delta-T fluctuation can be considered to reflect its effect on the tank capacity. The plant ChW flow rate is determined by the control strategy sub-model, which includes three conventional strategies.

The application of this method is illustrated with a practical project. The purpose of this project is to erect a new chilled water storage tank and share it among four chiller plants to reduce the utility billing costs. Based on the analysis on the historical data, utility rate structures, and equipment information, the electricity energy and billing cost baselines are generated. A simplified TES plus four plants model is built based on some assumptions. To find the optimal tank size and operation strategy, eight scenarios are designed and simulated. The simulation results and comparisons show that a 3.5 million gallon (13,249 m^3) tank is recommended as the optimal option. Full storage strategy is selected for the summer months and storage-priority strategy is selected for the winter months. The simple payback of this retrofit project is 12.5 years. A sensitivity study shows that the load factor is the most sensitive parameter to the payback time. If the loop delta-T is less than 9.5ºF (5.3 ºC), the payback time will increase.

NOMENCLATURE

C = cost, \$
CHLR = chiller
ChW = chilled water

CT = cooling tower
CWP = condenser water pump
FOM = figure-of-merit
GPM = gallons per minute
N = mnumber
P = power, kW
PLR = part load ratio
PPMP = primary pump
Q = cooling load, ton
R = electricity energy or demand rate, $/kWh or $/kW
SPMP = secondary pump
t = hour
T = temperature, ºF
TES = thermal energy storage
TOU = time-of-use
U = volume, gallon
V = flow rate, GPM
WTW = wire-to-water
x = tank ChW level ratio
Δt = time step, hour
ΔT = temperature difference, ºF

Greek symbols

ϕ = figure-of-merit
ξ = wire-to-water efficiency, kW/ton

Subscripts

Cap = capacity
d = demand
e = energy
k = current hour
Lp = loop
max = maximum
min = minimum
sp = setpoint
sys = system

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