Leveraging Thermal Storage to Cut the Electricity Bill for Datacenter Cooling*

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ABSTRACT

The electricity cost of cooling systems can account for 30% of the total electricity bill of operating a data center. While many prior studies have tried to reduce the cooling energy in data centers, they cannot effectively utilize the time-varying power prices in the power market to cut the electricity bill of data center cooling. Thermal storage techniques have provided opportunities to store cooling energy in ice or water-based tanks or overcool the data center when the power price is relatively low. Consequently, when the power price is high, data centers can choose to use less electricity from power grid for cooling, resulting in a significantly reduced electricity bill.

In this paper, we design and evaluate TStore, a cooling strategy that leverages thermal storage to cut the electricity bill for cooling, without causing servers in a data center to overheat. TStore checks the low prices in the hour-ahead power market and overcools the thermal masses in the datacenter, which can then absorb heat when the power price increases later. On a longer time scale, TStore is integrated with auxiliary thermal storage tanks, which are recently adopted by some datacenters to store energy in the form of ice when the power price is low at night, such that the stored ice can be used to cool the datacenter in daytime. We model the impacts of TStore on server temperatures based on Computational Fluid Dynamics (CFD) to consider the realistic thermal dynamics in a data center with 1,120 servers. We then evaluate TStore using workload traces from real-world data centers and power price traces from a real power market. Our results show that TStore achieves the desired cooling performance with a 16.8% less electricity bill than the current practice.

1. INTRODUCTION

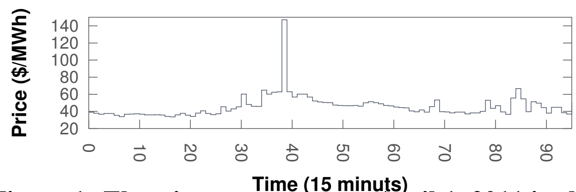


Figure 1: Electric power price on April 1, 2011 in the CAPITAL area of New York.

With the increasing high server density, cooling has been consuming a major portion of the total operational cost of datacenters (*e.g.*, 30% [10]). Reducing cooling cost, *i.e.*, the electricity bill for the energy consumed by the Computer Room Air Conditioning (CRAC) system, is an important concern for datacenter operators.

Many existing solutions (*e.g.*, [6, 2]) concentrate on reducing the cooling energy. However, the energy consumed at different time contributes differently to the cooling cost because the electricity price in the market may fluctuate significantly. As shown in Figure 1, in a market that provides the price in the next hour based on a bidding mechanism (hour-ahead market), the price is bellow $40/MWH between 0:00AM to 6:00AM and above $50/MWh between 9:00AM and 12:00AM. At 9:45AM, the price rises from $62.91/MWh to $147.11/MWh.

The fluctuation in the power price suggests a method to reduce the cooling cost using thermal storage techniques. First, various thermal masses in a data center, such as the cold air, the recirculation air handler coils, supply air ducts, and raised metal floor can be over-cooled by the CRAC system to a low temperature, such that they can absorb heat later as thermal reserve space [4]. Consequently, when the power price is high, data centers can choose to use less electricity from the power grid for cooling, resulting in a significantly reduced electricity bill. Second, some datacenters [1, 5] have started to adopt auxiliary tanks to store energy in the form of ice, chilled water, etc, for long-term (e.g., daily) thermal storage. However, the impacts of thermal tanks on the server temperatures in the datacenter and their potential on reducing electricity costs have not yet been analytically evaluated.

In this paper, we evaluate the potential cost savings of leveraging thermal storage in datacenter cooling. We design TStore, a smart cooling strategy that leverages thermal storage to cut the electricity bill for cooling, without causing servers in a data center to overheat. TStore integrates two different thermal storage techniques, on different time scales, to use less electricity for cooling when

*This work was supported, in part, by NSF under CAREER Award CNS-0845390 and Grant CNS-0720663.

HotPower '11, October 23, 2011, Cascais, Portugal.

the power price is high. TStore checks the low prices in the hour-ahead power market and overcools the thermal masses in the datacenter, which can then absorb heat when the power price increases later. On a longer time scale, TStore is integrated with thermal storage tanks to store energy when the power price is low at night. TStore quantifies the time and energy consumption to overcool a datacenter based on the analytical results from Computational Fluid Dynamics (CFD), a powerful mechanical fluid dynamic analysis approach. Specifically, this paper makes the following contributions:

- We establish a model between the temporary changes in cooling system settings (*i.e.*, the CRAC output temperature) and the cooling energy consumption.
- We use CFD to model the thermal dynamics of a data center to derive the energy losses when using the thermal masses inside the datacenter as a thermal storage system.
- We design TStore that integrates datacenter overcooling and thermal storage tanks to reduce cooling cost on both short and long time scales.
- We evaluate TStore in trace-driven simulations.

2. THERMAL STORAGE SYSTEM

As discussed in Section 1, TStore integrates two different thermal storage techniques: thermal masses in the datacenter and auxiliary thermal storage tanks.

On a short time scale, the thermal masses, *i.e.*, masses inside the datacenter such as the cold air, the recirculation air handler coils, can be used for thermal storage. The datacenter can be overcooled by adjusting the CRAC output temperature. The CRAC output temperature is adjustable via tuning the temperature of the water pumping into the CRAC units. The temperature of the water can in turn be tuned either by using a variable capacity compressor (for systems based on direct expansion units), or by modulating a chilled water supply valve (for systems based on water cooled units) [4], or by adjusting the amount of cold water pumped out from the auxiliary thermal storage. Compared with putting chillers on battery-based energy storage systems which can also be used to store energy on the short time scale, the thermal masses has almost negligible initial cost and lower operating cost, because it does not require purchasing additional equipment and replacing batteries frequently.

The major drawback for the thermal masses as a thermal storage system is that they can only store a limited amount of heat. Also, to keep the stored energy in the storage system, we need to keep the datacenter at a temperature lower the level required by the servers, which incurs energy waste. Thus, to minimize the energy losses, we only overcool the datacenter in a minimum length of time before the energy price increases and use all the

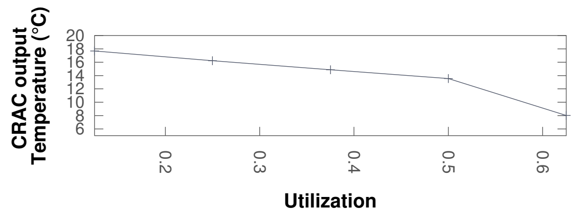


Figure 2: Traditional cooling strategy without thermal storage: tuning the CRAC output temperature to a level derived from offline profiling.

stored thermal energy in the thermal masses immediately after the price increases.

The auxiliary thermal storage tanks can be used to store energy at night and use it in daytime. In this paper, we assume an ice-based thermal storage tank [12]. The energy loss rate for a typical ice-based thermal storage tank can be analyzed as follows. First, a tank has an energy loss of about 1% to 5% per day caused by heat loss. Second, the energy loss for a chiller becomes more significant with a lower chiller output temperature. In order to turn water into ice for an ice-based tank, a chiller needs to cool the water to the phase change temperature of $0°C$, which is significantly lower than the temperature of the water used in water-based CRAC systems ($10°C$ to $17°C$) and thus incurs more energy waste. On the other hand, because the ice is made at night, the low temperature in the environment reduces the energy consumptions of the chillers. The transmission loss of the electric power becomes lower at night. Overall, considering all the energy losses and gains, a typical ice-based thermal storage system has an overall energy loss of about 13% [13]. Compared with battery-based energy storage systems, thermal storage tank-based system is usually a lower-cost solution, and is simpler and more reliable [1].

Note that the energy loss rate for a thermal storage tank becomes lower when better thermal materials are used in the tank. For example, if using phase change materials (PCM) such as hydrated salts with a phase change temperature of about $8.3°C$ [13] instead of water, the energy loss of the chiller becomes smaller.

3. SYSTEM MODELING DESIGN

In this section, we present the TStore strategy that uses the auxiliary thermal storage tanks on the long time scale (between day-time and night-time) and the thermal masses on the short time scale (*e.g.*, 15 minutes).

3.1 Traditional Cooling Strategy

We first assume that the datacenter has a traditional cooling strategy which tunes the CRAC output temperature to guarantee the cooling performance. Because the focus of this paper on reducing cooling cost using thermal storage systems, we assume a simple traditional cooling strategy as follows, while more sophisticated cooling strategies (*e.g.*, [16]) for energy reductions can be integrated with our cooling strategy as well. We simulate the datacenter running at different utilization levels as shown in Figure 2. For each utilization level, we manually tune the CRAC output temperature until the datacenter reaches the desired cooling performance proposed by [2], *i.e.*, the average inlet air temperature of the 80 hottest servers reaches $25°C$. We plot the CRAC output temperature in Figure 2. The traditional cooling strategy is to select a fixed CARC output temperature from Figure 2 based on the measured datacenter utilization.

3.2 Short-Term Overcooling

To reduce cooling cost by overcooling the datacenter before the energy price increases, it is important to quantify the increased cooling energy consumption when overcooling the datacenter and the decreased energy consumption after the overcooling process. Therefore, we first establish a model between the cooling energy and the CRAC output temperature. We then design our overcooling algorithm.

3.2.1 Cooling Energy

The cooling power of a datacenter can be modeled as [2, 6] :

$$CoolingPower = HeatRemoved/COP \qquad (1)$$

where COP is the coefficient of performance, a variable that depends on the output temperature of the air conditioning facility. We use a COP model from a chilled-water CRAC unit at the HP Labs Utility Data Center [6]:

$$COP(T_{out}) = (0.0068T_{out}^2 + 0.0008T_{out} + 0.458) \quad (2)$$

where T_{out} is the outlet temperature of the CRAC system.

The heat removed in (1) is calculated as [11]:

$$HeatRemoved = m * C_p * (T_{in} - T_{out}) \qquad (3)$$

where m is the mass flow rate. C_p is the specific heat, a constant number. T_{in} is the inlet temperature of the CRAC system.

Therefore, the cooling energy in each invocation period is:

$$\begin{aligned} Energy(k) &= \int_{kT}^{(k+1)T} CoolingPower(t)dt \\ &= \int_{kT}^{(k+1)T} \frac{m * C_p * (T_{in} - T_{out})}{COP(T_{out})} \end{aligned} \qquad (4)$$

The impacts of TStore on server temperatures, *i.e.*, how the CRAC input temperature T_{in} in (4) changes when adjusting the CRAC output temperature T_{out}, can be modeled based on CFD analysis. CFD is a fluid mechanics approach that analyzes problems of fluid flows based on numerical methods and algorithms. Several popular software, such as AirPAK and Fluent, can be used for CFD modeling purpose. These software packages allow modeling the thermal behavior of existing datacenters and quantify the temperature changes over time.

We derive the energy consumption to overcool the datacenter and the energy consumption after the datacenter returns to a traditional cooling strategy as follows. We first derive how T_{in} changes as a function of time. Therefore, we perform a series of experiments in the CFD simulation environment. We fix the utilization of the datacenter to a level (*e.g.*, 25%). For the datacenter cooled to a steady state with a traditional cooling strategy, we turn down the CRAC output temperature to different levels lower than the one required by the traditional cooling strategy and plot the temperature changes in Figure 3a. Similarly, we plot the temperature changes when the CRAC output temperature is turned from several low levels back to the level required by the traditional cooling strategy in Figure 3b. Then, as demonstrated in Figure 3c, for different depth of overcooling in terms of the CRAC input temperature, we derive the energy consumption to overcool the datacenter and the energy consumption when the datacenter returns from an overcooled state using the temperature curves in Figure 3a, 3b and Equation (4). We then repeat the process for all levels of datacenter utilizations.

3.2.2 Algorithm Design

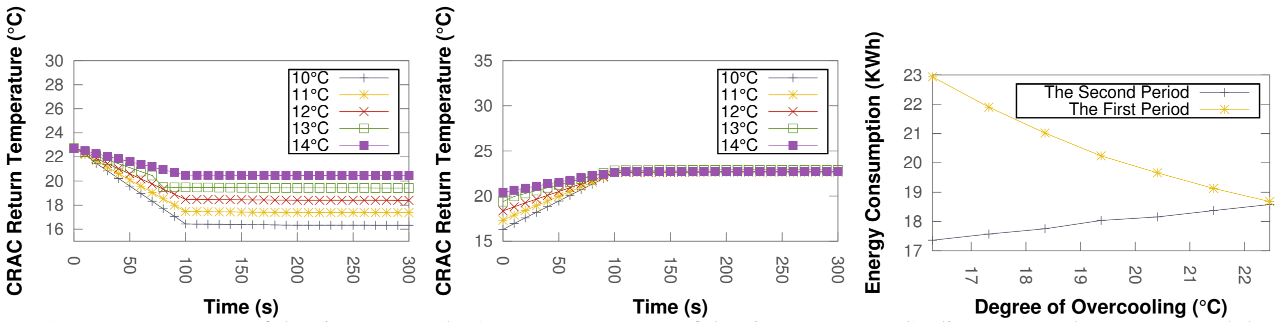
Our algorithm is invoked periodically with the same period that the price changes. In an offline profiling, we derive the energy consumption curve in two adjacent periods if we overcool the datacenter in the first period and return to the traditional cooling strategy in the second one, *i.e.*, a curve similar to Figure 3c, for every utilization level.

In every period, our algorithm checks the electricity price in the current period and in the next period in the power market. Then based on the current level of utilization in the datacenter, the algorithm checks the energy consumption curve (Figure 3c) and finds a degree of overcooling T_D with the least electricity cost in the two periods if we overcool the datacenter in the first period and return to the traditional cooling strategy in the second one.

Thus, our algorithm overcools the datacenter if the predicted cost is lower than the traditional cooling strategy. In order to use the minimum energy to achieve the desired depth of overcooling at the end of the current period, we use traditional cooling strategy between time kT and $(k+1)T - T_s$, and turns the CRAC output temperature to T_D from time $(k+1)T - T_s$ to time $(K+1)T$ where T_s is the settling time of the temperature of the datacenter.

Because our algorithm either uses the traditional cooling strategy, or uses a CRAC output temperature lower than the value that the traditional cooling strategy uses, our algorithm achieves the same or better cooling performance as the traditional cooling strategy does, *i.e.*, the temperature of the 80 hottest servers will not exceed the desired value of $25°C$.

Note that we assume that the electricity price in the near future is known, which is a valid assumption in several types of power markets such as the hour-ahead market. In other types of power markets, our algorithm can



(a) Average temperature of the air returning to the CRAC unit when the CRAC output temperature is turned down to precool the datacenter at time 0.

(b) Average temperature of the air returning to the CRAC unit after precooling.

(c) Cooling energy when we overcool the datacenter in the first period and return to the traditional cooling strategy in the second period. The degree of overcooling is plotted as the CRAC input temperature.

Figure 3: The energy consumption under different cooling strategies.

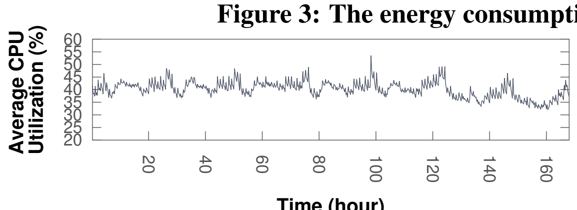


Figure 4: Utilization trace of the datacenter.

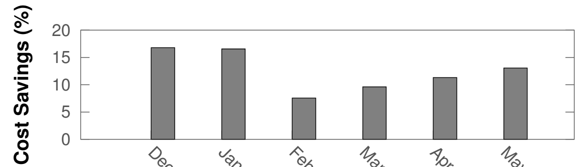


Figure 5: Cost savings of TStore compared with the traditional cooling strategy.

be integrated with price prediction algorithms [8, 9] to achieve short-term cost savings.

3.3 Long-Term Thermal Storage

We use the tanks to store energy in the form of ice when the power price is low at night, such that the stored ice can be used to cool the datacenter in daytime.

At the end of each day, based on the history of energy consumption and price in the day, the algorithm maintains two bars of price, H and L, based on the price and energy consumption everyday. The bar of L is calculated such that the time when the price is lower than L is enough to charge the tank to full. The bar of H is calculated such that the total energy that can be pumped from the tank in the time slots when the price is higher than H equals to the maximum usable capacity of the tank. Then in the next day, the cooling system pumps out cooling energy from the tank when the price is higher than H and charges the tank whenever the price is lower than L. At the same time, the CRAC output temperature is managed by the algorithm presented in Section 3.2 to guarantee the cooling performance.

4. SIMULATION ENVIRONMENT

We use AirPAK to simulate the cooling in a datacenter. We implement a simulated datacenter with 1120 blade servers using the configurations consistent with those used in several previous studies [2, 6, 7, 14]. The details of the datacenter are not shown here due to space limitations, but are available in [2]. The CRAC output temperature can be tuned within the range from $10°C$ to $17°C$ [11].

We assume that it takes 4 hours for the thermal storage tank to be fully charged based on a study to a similar ice-based storage system [3]. The tank incurs 13% of energy loss in a charge and discharge cycle [13]. Based on the parameters from a real thermal storage system [13], we assume the tank can store 21% of the day-time cooling energy, which is 738 KWh for our simulated datacenter.

5. EVALUATION RESULTS

We now perform simulations to demonstrate that TStore can achieve the desired cooling performance with less cost than the traditional cooling strategy.

In the first simulation, we use the price from the hour-ahead market in CAPITAL area of New York from Dec. to May 2011. We use a datacenter utilization trace with 5,145 servers [15] and map it to our datacenter by consolidating the utilizations of all the servers and distributing them evenly to our 1,120 servers as plotted in Figure 4. Note that we evenly distribute the utilization of the servers because we focus on cooling in this paper, more sophisticated workload distribution methods (*e.g.*, [2]) can be integrated with TStore.

For every 15 minutes, we calculate the cost savings using the model in Figure 3c, the price data, the datacenter utilization, the increased energy consumption when storing energy into the thermal storage system, and the decreased electricity energy consumption when using the energy in the thermal storage system. Figure 5 shows the cost savings of our TStore over the traditional cooling strategy. In these experiments, TStore achieves an energy saving of 12% on average.

To demonstrate our cooling performance, we perform a simulation of the transient state of the datacenter in 30 minutes. Figure 6 plots the average temperature of the 80 hottest servers. The datacenter is overcooled from time

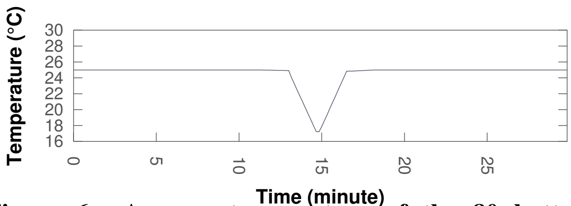


Figure 6: Average temperature of the 80 hottest servers in 30 minutes. The datacenter is overcooled from time 12.8m to time 15m and is turned to the traditional cooling strategy from time 15m.

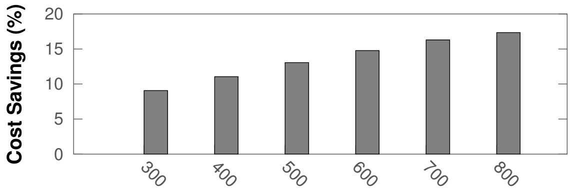


Figure 7: Cost savings of TStore in Dec. 2010 compared with traditional cooling strategy under different thermal storage tank sizes.

12.8 minutes to time 15 minutes and is then turned to use the traditional cooling strategy. In all the 30 minutes, the temperature is lower than the desired level of $25°C$. At time 14.8 minutes, the temperature is lowered to $17.23°C$ due to our overcooling algorithm.

Because the size of the thermal storage tank determines the initial equipment investment and how much energy can be stored, we perform a series of simulations using different tank sizes to demonstrate the trade-off between the tank size and the savings in electricity bill. As plotted in Figure 7, the cost savings increases from 9% to 17% as the tank size increases from 300 KWh to 800 KWh.

6. RELATED WORK

Datacenter cooling consumes a significant amount of energy. Several recent studies have focused on reducing the cooling energy consumption for data centers by scheduling the requests [2, 6] or by turning the CRAC settings [4, 16] without considering the electric price. Compared with these studies, we take a further step to reduce cooling cost by using less energy when the electricity price is high and using more energy when the price is low.

Thermal storage has been demonstrated to be able to effectively shift energy consumptions from time to time. For example, an Intel datacenter [1] uses chilled water tanks to cool the data center during power outage of the CRAC system. Several projects use thermal storage system to shift energy consumption from day time to night time [13] for cost reduction assuming that the electricity price changes from a peak price to a non-peak price everyday at a specific time. Compared with these industry projects, TStore analytically evaluates the impacts of thermal tanks on the server temperatures and the potential on electricity cost savings. Furthermore, TStore combines the short-term and long-term thermal storage for more cost savings.

7. CONCLUSION

While many prior studies have tried to reduce the cooling energy in data centers, they cannot effectively utilize the time-varying power prices in the power market to cut the electricity bill of data center cooling. In this paper, we propose TStore, a smart cooling strategy that leverages thermal storage to cut the electricity bill for cooling, without causing servers in a data center to overheat. TStore checks the low prices in the hour-ahead power market and overcools the thermal masses in the datacenter, which can then absorb heat when the power price increases. On a longer time scale, TStore is integrated with thermal storage tanks to store energy when the power price is low at night. Our trace-driven simulation show that TStore achieves the desired cooling performance with a 16.8% less electricity bill than the current practice.

8. REFERENCES

[1] Thermal storage system provides emergency data center cooling. Technical report, Intel, 2007.

[2] F. Ahmad et al. Joint optimization of idle and cooling power in data centers while maintaining response time. *ACM SIGARCH Computer Architecture News*, 38(1):243–256, 2010.

[3] L. E. BASGALL. Thermal energy storage design for emergency cooling. Master's thesis, Kansas State University, 2008.

[4] T. Boucher et al. Viability of dynamic cooling control in a data center environment. *Journal of electronic packaging*, 128:137, 2006.

[5] R. L. Mitchell. Ice balls help data center go green. http://www.computerworld.com/s/article/9190160/Ice_balls_help_data_center_go_green, 2010.

[6] J. Moore et al. Making scheduling "cool": temperature-aware workload placement in data centers. In *USENIX*, 2005.

[7] J. Moore et al. Weatherman: Automated, online and predictive thermal mapping and management for data centers. In *ICAC*, 2006.

[8] F. Nogales et al. Forecasting next-day electricity prices by time series models. *Power Systems, IEEE Transactions on*, 17(2):342 –348, may 2002.

[9] F. Nogales et al. Electricity price forecasting through transfer function models. *Journal of the Operational Research Society*, 57(4):350–356, 2005.

[10] S. Pelley et al. Understanding and abstracting total data center power. In *WEED*, 2009.

[11] C. P. Ratnesh et al. Thermal considerations in cooling large scale high compute density data centers. In *In ITherm 2002*, 2002.

[12] K. Roth et al. cool thermal storage. *ASHRAE Journal*, 48:94, 2006.

[13] K. W. Roth et al. Energy consumption characteristics of commercial building HVAC systems volume III: Energy savings potential. http://doas-radiant.psu.edu/DOE_report.pdf, 2002.

[14] R. K. Sharma et al. Balance of power: Dynamic thermal management for internet data centers. *IEEE Internet Computing*, 9:42–49, January 2005.

[15] X. Wang et al. SHIP: Scalable hierarchical power control for large-scale data centers. In *PACT*, 2009.

[16] Z. Wang et al. Optimal fan speed control for thermal management of servers. In *ASME*, 2009.